MAN and
his FUTURE

हे पुस्तक मोडत असल्यास
साधारण ... बाद होईल

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# PHYSICAL SCIENCE




*Frontispiece*

# THE RECENT DEVELOPMENT OF PHYSICAL SCIENCE

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# PREFACE

In recent years we have witnessed a great development of physical science. The different sections into which physical knowledge is, for the sake of convenience, divided, have grown each within its own domain; and, moreover, have shown increasing signs of extending beyond the boundaries arbitrarily traced between them. The methods of physics, in the restricted sense of that word, are being more and more applied to chemical and biological problems, while many questions in physics can only be investigated by those with mathematical or chemical training.

Thus it happens that an acquaintance with the knowledge newly acquired in one department of science is necessary for the study of another; indeed, the phenomena which need for their interpretation the methods of two branches of science have proved often the most fruitful field of inquiry.

For reasons such as these it has been thought

possible that a short account of some of the important investigations now being carried on in the physical laboratories of the world might prove useful to students of science in general; while it is hoped that, by treating the subjects as far as possible without technical language, the book may also appeal to those who, with little definite scientific training, are interested in the more important conclusions of scientific thought.

The writer has been fortunate in his surroundings, where the knowledge and insight of one worker are freely and ungrudgingly placed at the service of another in the day of his need. In the present undertaking he records gratefully the help of several friends who have read the proof sheets of the parts dealing with subjects with which their names are closely associated. Mr. F. H. Neville criticised the chapter on The Philosophical Basis of Physical Science, and that on Fusion and Solidification. Lord Berkeley read the account of The Problems of Solution. Professor J. J. Thomson saw the manuscript of the original article on which is founded the chapters on Conduction of Electricity through Gases and

Radio-Activity. Professor Larmor revised the account of Atoms and Æther, while Mr. H. F. Newall read the chapter on Astro-Physics. For this assistance the writer expresses his cordial gratitude. He wishes especially to thank his wife for continual correction both of the manuscript and of the proof sheets, and his sister for help with the index.

The editor of the *Quarterly Review* has kindly allowed use to be made of the article on Matter and Electricity which appeared in January 1904. Professor George E. Hale was good enough to permit some of his photographs of the sun to be reproduced, while, for other illustrations, acknowledgments are due to the Royal Society, to Mr. Heycock and Mr. Neville, and to Mr. G. T. Beilby. Lord Kelvin kindly sent a signed portrait, and Professor J. J. Thomson allowed the use of a reproduction of Mr. Arthur Hacker's admirable painting, which now hangs in the Cavendish Laboratory.

In spite of the generous help he has received, the author is sadly conscious of the difficulty of his task. Although the development of physical science is one of the most powerful activities of our time, a knowledge of its aims, methods, and

results has not yet been recognised as a necessary part of an English liberal education. To give a popular exposition of results, especially when there is an obvious technical application, is easy; to enable a non-scientific mind to follow and appreciate the methods by which the results are reached is supremely difficult. But in science methods are usually more important than results, while a superficial acquaintance with results without an underlying knowledge of method is useless, or worse than useless.

In the possibility of treating the wider and deeper generalisations of natural science as fit subject-matter for current thought and literature, the writer has a profound belief. Whether the failure to secure such treatment has been due to lack of adequate exposition, or to some radical defect in the training of the nation, is a difficult and grave problem; but, until the point of view has been altered, it is perhaps hopeless to look for a proper understanding of the scientific spirit and of scientific method even among the more educated portion of the community. For the present, the man of science must perforce occupy a more technical and isolated position than the

student of history or the lover of art. From the point of view of the man of science, to break down this isolation would be, at best, but sorry kindness; but, from a wider point of view, for the good of the nation and of mankind, a more general acceptance of a share in the impersonal open-minded search for truth, which is the essence of science, is ardently to be desired.

With some such thoughts as these, the writer sends forth the following pages.

CAMBRIDGE, *June* 25, 1904.

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# PHYSICAL SCIENCE

"Not clinging to some ancient saw;
Not mastered by some modern term;
Not swift nor slow to change, but firm:
And in its season bring the law."

—TENNYSON.

IN the great advance of recent years, Physical Science has developed chiefly in two directions. Although these movements have been contemporaneous, it is interesting to note that the methods employed by the two schools of research are, to some extent, the expression of opposite tendencies.

On the one hand, we see the growth of the study of the phenomena of equilibrium in physical and chemical systems; this growth is due to the thermodynamic methods founded chiefly on the great work of the late Willard Gibbs, of Yale University in the United States. On the other hand, our knowledge of the mode of the conduction of electricity through gases has been extended, mainly by the efforts of J. J. Thomson, Professor of Experimental Physics at Cambridge, and of the band of workers trained by him in the Cavendish

Laboratory. Of late years students from almost all civilised countries have come to Cambridge as to the centre of this branch of physical research, and many of them are now carrying forward their investigations elsewhere, by methods learnt in the University of Newton, Clerk-Maxwell, and Stokes.

As we shall see in the following pages, the work of this school of physicists is undertaken and interpreted by the aid of atomic and molecular conceptions. The theory of the conduction of electricity through liquids, based originally on the work of Faraday, and slowly matured during the last half-century by Hittorf, Kohlrausch, Arrhenius, and many others, had accustomed our minds to the conception of electric conduction by means of the motion of charged particles, called by Faraday "ions"—the travellers. Each ion consists of an atom, or group of atoms, of the substance in solution, associated with a positive or negative electric charge; it moves through the liquid under the action of an applied electric force, and gives up its charge to the electrode—that is, the terminal by which the current enters or leaves the liquid. The conduction, instead of being conceived as a river flowing uniformly, must figuratively be represented as taking place by the passage of discrete quantities of electricity; in much the same way as water is sometimes

carried from a lake to a burning house by means of a chain of bucket-bearers.

By the application of similar conceptions, the passage of electricity through gases has received a convincing explanation. Differences appear, but the fundamental ideas are the same in the two branches of the science of electrolytic conduction. It is, however, in the newer side of the subject that the most striking results have been obtained. Electrolysis in liquids had suggested the conception of ultimate units of electricity — atoms of electricity, analogous to the atoms of matter. Gaseous conduction enabled these electric atoms to be isolated, separated from their attendant material atoms, and studied independently.

Great has been the revelation which followed. The isolated atoms of negative electricity — the electrons, as they have been named by Stoney — have been identified by the work of Thomson, Lorentz, and Larmor, with the physical basis of matter, with the corpuscles, or sub-atoms, by means of which, combined in varying numbers and in different arrangements, are composed the chemical atoms, for long taken as ultimate indivisible units.

Farther light has been thrown on these dark places by the remarkable series of discoveries through which M. and Mme. Curie and other

chemists have given us the radio-active elements such as radium, and the parallel series in which Rutherford has interpreted their properties as due to the disintegration of their atoms, as, one after another, those atoms break down, and are transmuted into other substances.

Throughout these investigations we deal with atomic and molecular conceptions in an extreme form. We look even within the atom, and examine its internal structure; we trace the corpuscles or electrons flying round in their orbits, as we watch the planets swinging round the sun.

It is remarkable that, in the other branch of Physical Science in which simultaneous progress has been most striking, the methods chiefly employed have enabled us to dispense altogether with atomic and molecular theories.

At the basis of the theory of physical and chemical equilibrium lies Lord Kelvin's great principle of the dissipation of energy. While the total amount of energy in an isolated system is unchanging and unchangeable, that energy is tending always to become less available for the performance of useful work. The availability of the energy tends continually to become less. It follows that permanent equilibrium can only be attained when the limit has been reached and the availability is a minimum. Such a theorem

is independent of molecular hypotheses; in fact, it expressly disclaims such hypotheses, for, as Maxwell showed, the chance collisions of the individual molecules in a gas will lead to differing molecular velocities, and to a concentration of energy in the fast-moving molecules. If we could follow the motions of the individual molecules, and separate the fast from the slow, we could use this energy. The principle of dissipation, therefore, only holds while we are obliged, as of course is always the case in practice, to deal with molecules statistically and in the aggregate.

The principles thus applied to isolated systems have been extended to the visible universe. Predictions have been made that ultimately the energy of the universe will become completely unavailable, and will settle down into the energy of heat, uniformly distributed. But this final sleep of the universe depends on the assumptions that the universe is an isolated system, finite in extent, and that no process of molecular concentration of energy, such as was imagined by Maxwell, is going on anywhere throughout the depths of time and space.

A more restricted, though more fruitful, application of the dissipation principle enabled Helmholtz, and, in a much more general manner,

Willard Gibbs, to place on a firm footing the theory of non-isolated but isothermal systems—systems, that is, maintained at a uniform and constant temperature by the gain or loss of external heat. The external work which such a system can perform, by means of a reversible change at constant temperature, tends to a minimum, and the system is in permanent equilibrium when, and when only, this available or free energy, as it is called, becomes as small as possible. By this sole principle, Willard Gibbs developed the complete theory of chemical and physical equilibrium; as Professor Larmor says, his "monumental memoir made a clean sweep of the subject; and workers in the modern experimental science of physical chemistry have returned to it again and again to find their empirical principles forecasted in the light of pure theory, and to derive fresh inspiration for new departures."

Simultaneously with the development of experimental research along the two lines we have indicated, has arisen afresh an interest in and inquiry into the philosophic basis on which is built the whole magnificent structure of modern science. How far is that basis secure? Are the conceptions of science life-like pictures of any fundamental reality behind the phenomena which alone our senses can apprehend? Such questions

have occupied periodically the ablest minds of certain epochs of history, though in the attempts to find answers no such general consensus of opinion has been reached as we see within the building of science itself. Granted the security of the foundations, the edifice seems designed on a consistent plan, for the relations of its parts present themselves similarly to all minds competent to judge.

The philosophy of science is intimately connected with its history; and interest has been stimulated afresh in the philosophical problems involved in physical conceptions by the publication of Mach's great work on the Science and History of Mechanics. To many that book has put new life into the subject treated in its pages, and has led to a more careful consideration of the fundamental conceptions of natural science in general.

In the following pages an attempt will be made first to consider the philosophic foundations of physics, and then to trace some of the more important developments of the experimental investigations for which the last few years have been remarkable.

The study of physical equilibrium—the equilibrium between different states or phases, solid, liquid, and gaseous, of the same substance—

naturally opens with the consideration of the relations between the different states of pure chemical elements and compounds. Here, the most striking recent work is the liquefaction of air and hydrogen, with which the name of Dewar most prominently must be associated.

Next we turn to mixtures, and the fusion and solidification of solutions and alloys claim our attention. The microscopic analysis of metals, when elucidated by the theory of equilibrium, has had far-reaching influence on the practical arts of metallurgy.

Then are considered the problems of solution in general, without restriction to conditions of equilibrium. Now, for the first time, we come in contact with electrical phenomena; and the theory of ionic conduction throws light, not only on the nature of electrolytic solutions, but on many physiological questions of vital interest.

A natural step leads from the conduction of electricity in liquids to its conduction in gases, and, on our stage, the ion is joined by the corpuscle or electron. The dream of the old philosophers of a common basis for matter is realised by experimental investigation.

Arising from these experiments and their interpretation comes the theory of radio-activity, the modern equivalent of the imagined transmutation

of the mediæval alchemist. Though the changes are beyond our control, we see and measure the gradual evolution and disintegration of the chemical elements, and draw on the energy stored within the atoms themselves.

The vibrations of electro-magnetic systems produce the æthereal waves now used in wireless telegraphy, and the vibrations of atomic systems give rise to light. Thus atoms must be intimately related to the luminiferous æther, and light to electro-magnetic phenomena. Corpuscles or electrons, too, cry aloud for a physical explanation in terms of æthereal conceptions ; and Larmor's idea of an electron as a centre of intrinsic æthereal strain gives us a possible formulation of the subject, and, in some form or other, seems now to hold the field.

Finally, we pass to the bearing of all this new knowledge on cosmical problems. Physics is rapidly annexing the domain of astronomy, as it has already invaded the realms of chemistry and biology. By the aid of the spectroscope we examine the chemical nature of the sun and stars, we measure the rates of their motions and revolutions, and obtain data from which we may speculate about their origin, development, and decay. From the internal structure of the atom to the majestic progress of the suns, the investiga-

tions of Physical Science are surely and continuously gaining new knowledge for mankind.

We scatter the mists that enclose us,
  Till the seas are ours and the lands,
Till the quivering æther knows us,
  And carries our quick commands.
From the blaze of the sun's bright glory
  We sift each ray of light,
We steal from the stars their story
  Across the dark spaces of night.

But beyond the bright search-lights of science,
  Out of sight of the windows of sense,
Old riddles still bid us defiance,
  Old questions of Why and of Whence.
There fail all sure means of trial,
  There end all the pathways we've trod,
Where man, by belief or denial,
  Is weaving the purpose of God.

# CHAPTER I

## THE PHILOSOPHICAL BASIS OF PHYSICAL SCIENCE

"Homo, naturæ minister et interpres, tantum facit et intelligit quantum de naturæ ordine re vel mente observaverit. . . . Natura enim non nisi parendo vincitur. . . ."—BACON, *Novum Organum*.

THE mind of man, learning consciously and unconsciously lessons of experience, gradually constructs a mental image of its surroundings—as the mariner draws a chart of strange coasts to guide him in future voyages, and to enable those that follow after him to sail the same seas with ease and safety. The chart may be drawn to scale; it may be consistent with itself and serve its purpose—but it only represents the earth's surface in one limited and conventional manner; it does not give a life-like picture of the original in the same sense as does a photograph or a painting. So it is with the ideas that our minds conceive of the world around us, and with the model of that world which our minds construct. And this analogy may serve to interpret to us our attitude towards the conception that the human race has formed of the world we live in. If the model be consistent, if the various

parts and aspects of it do not fail to correspond with each other, it serves the double purpose of introducing order into what would otherwise be mental confusion, and of helping us to make systematic use of the resources of Nature.

Confronted with the mystery of the Universe, we are driven to ask if the model our minds have framed at all corresponds with the reality; if, indeed, there be any reality behind the image. Such a question is a proper study of philosophy, but need not necessarily be answered for the model to be made or used. The whole problem mankind has to face undoubtedly includes this fundamental question of the ultimate nature of reality, which would enter into a complete explanation of every fact, even of those which we regard as the simplest. This general aspect of the problem is the subject of that branch of philosophy known as Metaphysics. But, if we confine our attention to the phenomena which our senses apprehend, and, thus restricting our inquiry, examine our mental picture of Nature and the relation of its parts to each other, testing their correspondence or want of correspondence, we are studying Natural Science. The limitation indicated has not always been observed, and the name of Natural Philosophy survives to remind us that Natural Science is but one part of the whole of conceivable knowledge.

The problem of Metaphysics is of much greater difficulty than that of Natural Science. Hence, Natural Science has only begun to make rapid progress since its separation from Metaphysics. Despite the closest attention of the acutest intellects since the age of Greece, no general consensus of opinion has been reached by metaphysicians. Materialism, Dualism, Idealism, inconsistent views of the nature of reality, are all of them still held by competent philosophers :

> " Myself when young did eagerly frequent
> Doctor and saint, and heard great argument
> About it and about : but evermore
> Came out by the same door where in I went."

The slow and laborious methods of observation and experiment have been pursued from the earliest times for purposes of common life and technical industry. They were first considered philosophically though inadequately by Bacon, and by their help a firm ground has been obtained for the edifice of Natural Science. In contrast with the results of Metaphysics, a general consensus of scientific opinion upon fundamental points has been obtained. No physicist of repute doubts the validity, within narrow limits of error, of Newton's law of gravity, or of the principle of the conservation of energy.

But observation and experiment can be directed

only to the examination of our conceptions. In this way we gain materials for the construction and examination of the mind's model of reality; we do not touch reality itself. If this be doubted, we must reflect that we can apprehend the results of experiment through our senses alone. Though, for instance, the galvanometer seems at first to supply us with a new electrical sense, on further thought we see that it merely translates the unknown into a language our sense of sight can appreciate, as a spot of light moves over a scale. It is possible that Philosophy may take into account knowledge which reaches us by means other than the senses. Intuitions, fundamental assumptions, mental processes generally, doubtless have an external aspect, and may be studied by the science of Psychophysics, but they may have also another aspect in their internal relations to consciousness. Here they can be examined by Metaphysics. But we can only study Nature through our senses—that is, we can only study the model of Nature that our senses enable our minds to construct; we cannot decide whether that model, consistent though it be, represents truly the real structure of Nature; whether, indeed, there be any Nature as an ultimate reality behind its phenomena.

In emphasising the essential distinction between Natural Science and Metaphysics, we must not sup-

pose that the results of Natural Science have no metaphysical import. The possibility of putting together a consistent mental model of phenomena is a valid metaphysical argument in favour of the view that a consistent reality underlies those phenomena, and that the reality is represented with more or less faithfulness by the mental picture we have pieced together. Such an argument must carry great weight, and may, perhaps, be considered conclusive; but it is a metaphysical argument, not one with which Natural Science is concerned directly. In framing and attempting to answer her own deeper questions, Metaphysics uses the results of Natural Science, as indeed of all other branches of inquiry. But this does not make Natural Science a branch of Metaphysics, or remove the essential difference between the subjects of the two studies.

The object of Natural Science, then, is to fit together a consistent and harmonious model which shall represent to our minds the phenomena which act on our senses. We need not fear that this limitation will lower the dignity or circumscribe unduly the extent of our inquiries. Whether we look inwards or outwards the complexity of Nature seems boundless:

> "Boundless inward in the atom; boundless outward in the whole."

The more we learn, the more various and intricate are the new avenues of research which open before us. As has been well said, the larger grows the sphere of knowledge, the greater becomes its area of contact with the unknown.

So complex would be an entire mental picture of phenomena, that divisions of Natural Science have arisen, each of them tending more and more to demand the exclusive attention of the specialist. These divisions are purely arbitrary; they have arisen partly from differences in methods of inquiry, partly from historical reasons. Moreover, they are variable, and are shifted from time to time according to the needs of each department and the prevalent direction of inquiry, while new divisions may spring into existence.

The different sciences are not even parts of a whole; they are but different aspects of a whole, which essentially has nothing in it corresponding to the divisions we make; they are, so to speak, sections of our model of Nature in certain arbitrary planes, cut in directions to suit our convenience. Thus a nerve-impulse may be considered in a psychological aspect, a physiological aspect, or a physical aspect. Even these divisions may be subdivided; the physics of the nerve impulse may be studied first from the electrical side by investigating the electric currents that accompany it, and

then from the mechanical side, by correlating the electrical currents with the movements of matter that simultaneously occur. No one of these aspects of the phenomenon is essentially more fundamental than any other, and the conviction at one time prevalent, and even now by no means uncommon, that a complete mechanical explanation of every phenomenon is possible and fundamental, seems merely an unphilosophical fallacy. Its origin is to be sought in the historical fact that the section known as mechanics was the earliest of the physical sciences, and that its methods and conclusions are fairly intelligible to the ordinary man, and, in their elements, essential to his daily life. The science of mechanics has been more fully developed from its experimental basis by the methods of mathematical deduction than any other branch of Natural Knowledge, and mankind has hence come to believe that it is essentially simpler and nearer reality. But in truth it is no more fundamental than electricity, and, as we shall see in the following pages, there is a growing tendency in modern thought to conceive matter itself as an electrical manifestation.

Again, it is sometimes argued that mechanics is the fundamental science because its extension is universal, while that of physiology, for example, is not. The contraction of a muscle has clearly a mechanical aspect, while the fall of a stone to the

earth has nothing to do with physiology. Even a thought, from one side purely a psychological phenomenon, may have a mechanical aspect if we could trace the physical changes in the brain which accompany it, whereas, it may be said, the expansion of steam in an engine has no psychological significance. Such considerations certainly indicate that the arbitrary plane cut through our solid model of the universe by mechanical science is cut in such a place that it traverses a large part of the model—a larger part, perhaps, than any other section which has yet been cut. It does not follow, however, that it cuts through the whole; still less that a plane section can represent fully a solid model. Thus the argument that, because of its wide extension, mechanics has some fundamental significance is seen to be a fallacy. It may be *prima inter pares* of the natural sciences, but nothing more. To go even further than this, as has sometimes been done, and to suppose that the ultimate nature of reality is the same essentially as our idea of a single arbitrary section, cut through an imaginary model of it, seems only to need stating in these terms to be disbelieved.

As Mach has well said, "Physical Science does not pretend to be a complete view of the world; it simply claims that it is working towards such a complete view in the future. The highest philo-

sophy of the scientific investigator is precisely this toleration of an incomplete conception of the world and the preference for it rather than for an apparently perfect but inadequate conception."

When the experimental study of nature was new, when man first caught a glimpse of order in the multiplicity of phenomena, such a view of the all-comprehending character of mechanical science seemed just. Let us again listen to Mach :—

"The French encyclopædists of the eighteenth century imagined they were not far from a final explanation of the world by physical and mechanical principles; Laplace even conceived a mind competent to foretell the progress of nature for all eternity, if but the masses, their positions, and initial velocities were given. In the eighteenth century, this joyful over-estimation of the scope of the new physico-mechanical ideas is pardonable. Indeed, it is a refreshing, noble, and elevating spectacle; and we can deeply sympathise with this expression of intellectual joy, so unique in history. But now, after a century has elapsed, after our judgment has grown more sober, the world-conception of the encyclopædists appears to us as a mechanical mythology in contrast with the animistic mythology of the old religions. Both views contain undue and fantastical exaggerations of an incomplete perception. Careful physical inquiry will

lead, however," to a more complete philosophy. "The direction in which this enlightenment is to be looked for, as the result of long and painstaking research, can of course only be surmised. To anticipate the result, or even to attempt to introduce it into any scientific investigation of to-day, would be mythology, not science."

Physical Science, then, the subject of the present work, is merely one aspect from which we may agree to look at the model of Nature that our minds construct. It ignores the biological standpoint, from which phenomena are regarded in their bearing on life; it ignores the psychological standpoint, from which they are studied in relation to mind. With these limitations, let us see what kind of model of Nature we are led to build.

The ideas of length and time may be regarded as primary—length as the simplest form of space conception, time as a recognition of sequence in our states of consciousness. One of the earliest advances in exact science was the power of counting and the resultant method of expressing quantities as numbers. In spite of its essential nature, the capacity for so doing is by no means innate; nor is it even yet properly developed among all the races inhabiting this globe. In order to measure quantities, it is necessary to choose or invent some

unit, and then to count the number of times that unit is comprised in the quantity to be measured. In civilised countries the unit of length is taken as the length between two marks on a certain standard metallic bar. In England there is a standard yard, and in France a standard metre. In fact, both these units are arbitrarily selected for their convenience, though the original idea of the metre was derived from a connection with the supposed dimensions of the earth.

Like the unit of length, the unit of time is arbitrary, and ultimately rests on a measure of our sequence of consciousness. Again we have to choose some arbitrary unit, which, in this case, should always contain, under similar conditions, a similar amount of human consciousness. For purposes of the convenience of daily life the obvious unit to select is the day, while the sequence of the seasons suggests another equally arbitrary unit —the year. The exact relation between these two units can only be determined by careful astronomical observation. Wrong determination and consequent re-determination have led from time to time to necessary changes of calendar; while the partial adoption of these changes has resulted in the inconvenient differences of date in vogue among the various nations. That the units of time cannot be regarded as essentially fixed and unalterable is

clear when we remember that any friction on the earth, such as that of the tides, is slowly prolonging the day, while resistance to the bodily motion of the earth round the sun would gradually alter the length of the year. Such changes may become appreciable only after the lapse of thousands or millions of years; but the possibility of their occurrence shows that our time-units are as purely arbitrary as are those of length.

From the conceptions of length and time, and the arbitrary units chosen to measure them, may be derived the more complex ideas required for a description of motion, and the derived units needed to investigate it quantitatively. Thus velocity is measured by the ratio of the number of units of length to the number of units of time, while acceleration, or the rate of change of velocity, is measured by the number of units of velocity gained or lost per unit of time. These relations are expressed by saying that the dimensions of the unit of velocity are L/T, while those of the unit of acceleration are v/T or $L/T^2$.

With metaphysical theories of matter, Physical Science has no direct concern; and mechanics, at any rate, deals only with matter as that conception, which, in our mental image of phenomena, is always associated with another and more definite conception, that of mass. We need not ask whether

matter has any objective existence, or whether our conception of mass corresponds with any actual property possessed by a real thing-in-itself. Such inquiries are of great interest and importance; but they are metaphysical inquiries, not those which the physicist, as physicist, must answer.

The conception of mass, as distinct from that of weight, may arise from the results of our daily experience. Let us suppose, for instance, that two wheels of the same size, one of wood and the other of iron, were mounted on axles, and were free to revolve. When the wheels are set in motion, the weights do not come into play, for neither wheel is raised or lowered as a whole. Nevertheless, a great difference will be felt if we try to set the two wheels in motion suddenly. It takes either a much harder push or a much longer time to produce a certain velocity of rotation in the iron wheel than in the one made of wood. It is this result which leads us to say that the mass of the iron wheel is the greater.

To examine mass quantitatively, and to obtain a convenient unit, more definite observation is necessary. The mutual action of two bodies, as examined by experiment, is such that our description of their relative motion becomes greatly simplified by assigning to each of them a certain relative number to express a quantity which we may term

its relative mass. Let us make the two bodies, when free to move, act on each other in any way, excluding the possibility of rotation, for the sake of simplicity. Let us, for instance, connect them by means of a long, stretched elastic cord, and allow them to move each other. After the action has begun, we shall find that one body is, in general, moving faster than the other, and that the ratio of their accelerations is constant. The inverse ratio of these accelerations is the measure of the ratio between the masses of the two bodies; the body with the smaller mass is moved faster by the mutual action than is the body with the greater mass.

We now need only to choose some mass as our unit with which to compare other masses, and to prove experimentally that the mass of a body as thus defined is a constant quantity, to complete our preparations for using the conception of mass in our physical description of observed phenomena.

Experience shows us that we can generalise the result of our experiment on the motion of the two bodies connected with each other by means of a string. We can assert that no body has an acceleration unless another body is acting on it. Thus, we cannot form a complete picture of the motion unless we consider both bodies. But it is often necessary to concentrate our attention on

one of them, and it is then convenient to find some quantity which correctly measures the effect of the other body on the first. This quantity is not the acceleration, for that depends on the mass of the moving body, but it is the product of the mass and the acceleration, and is independent of both. This product completely records the mechanical effect of the second body; we call it a force, and instead of saying that one body is acted on by another, we may, if more convenient, say that it is acted on by a force.

Together with the primary conceptions of length, time, and mass, the secondary conception of force was employed by Newton in his development of mechanical theory. A simultaneous and parallel development of the science was led by Huygens, who used the conception which we now call work or energy as a means of co-ordinating the phenomena, instead of stating them in terms of force as Newton did. Although it gave a more intimate insight into mechanical processes, Newton's method was perhaps less general than that of Huygens, which often enables us to pass directly from a knowledge of the initial to a prediction of the final state of a system, and to avoid the difficulties of tracing its intermediate operations. In the history of mechanical science, now one method and now the other has proved the more useful;

and, in the wider field of physics, the two schools are still represented by those who seek to trace the intimate processes of change by means of molecular theories, and by those who rely on a more general presentment, which avoids such hypotheses by the use of the principles of thermodynamics.

By simple experiments, such as those described above, the relative masses of two reacting bodies may be measured by the constant inverse ratio of their accelerations. It follows that the product of the mass and the acceleration is the same for the two bodies. Thus the force which the first body exerts on the second is the same as the force which the second exerts on the first; or, as Newton expressed it, action and reaction are equal and opposite.

In the ways we have now considered, mass and force may be defined in a manner free from all metaphysical subtleties, and in these senses alone should they be used in physical science. A definition of matter is not needed: an inquiry into the so-called properties of matter being, from the physical point of view, an investigation into the phenomena which are associated with mass.

The conception of mass, in the present sense of the word, we owe to Newton: before his day no clear distinction was made between mass and

weight. We cannot predict whether mass, as defined above, has any relation to weight; any discovery of a connection between them must be a matter of experiment.

Weight is the force between the earth and the body considered, the product of the mass and acceleration being the same for the earth as for the body. If the forces were equal, the accelerations towards the earth of two bodies would, by our definition of mass, be inversely proportional to their masses. By experiments on the acceleration, then, the forces may be determined. Now it was shown by Galileo that, if the resistance of the air be eliminated, bodies fall at the same rate to the earth; that is, that the accelerations of all bodies to the earth are the same. It follows that the forces, that is, the weights of the bodies, must be proportional to the masses. Masses can thus be compared by weighing, and this method is much the most convenient in practice. Nevertheless, it must always be remembered clearly that the proportionality between mass and weight, and the consequent possibility of comparing masses by means of the balance, is not a relation which could be predicted *a priori*, but one which has been established as the result of careful experimental investigation.

When we turn from mechanics to the other

branches of physics, it is necessary, in the present state of knowledge, to use certain other fundamental conceptions, such as temperature and quantity of electricity, though it is probable that ultimately these will be connected with the mechanical units. Again, in this place it should be remarked that such a connection would not show that mechanics is necessarily the more fundamental science: it would be quite as correct, when the connection is established, to express mechanical quantities in terms of electricity or temperature.

This example leads us to state in a general form the immediate object of Physical Science. The physicist seeks to discover the relations between different phenomena, considered in one limited aspect, and to express those relations in a definite quantitative way. Our minds, led by the analogy with their own volitions, usually think of one of the related phenomena as the cause, and of the other as the effect. The physical equation which expresses the dependence of A on B, or, in symbols, $A = f(B)$, may equally well be written in the inverse form, by which B is asserted to be a function of A. In such cases, there is probably no philosophical distinction between cause and effect; it is no more right to say that an increase of pressure produces a decrease of volume in a gas than to say that a

decrease of volume produces an increase of pressure. The student merely discovers by experiment that the two phenomena accompany each other in every case investigated, and sums up the results of experience in conceptual language and in a short-hand form, in order to save the detailed investigation of each future individual case.

In these examples, the needlessness of the ideas of cause and effect will be fairly clear, as well as the confusion of thought sometimes brought about by their introduction. It is where the element of time is involved that the idea of causation is most vivid. When one of the two related phenomena follows the other, the mind instinctively identifies *post hoc* with *propter hoc.* And, even if such a distinction is philosophically unnecessary, as a matter of convenience in language it is perhaps justified. When carefully examined, however, the difficulty of isolating the "cause" of any particular "effect" will be found to be insuperable. A long train of circumstances has preceded the phenomenon considered, and the phenomenon would not have appeared had any one of those circumstances been absent. Each or all of them might equally well have been called the "cause." Whether the idea of cause and effect represents a real distinction in the hypothetical world which our conceptions represent, remains, like the nature

and existence of that world itself, an inquiry for the philosopher.

Physical Science, then, seeks to establish general rules which describe the sequence of phenomena in all cases. Underlying all such attempts is the belief that such an orderly sequence is invariably present, could it only be traced. This belief, which is the result of constant experience, is known as the principle of the Uniformity of Nature. In its absence no organised knowledge could be obtained, and any attempt to investigate phenomena would be perfectly useless. Unless, to use the conventional language justified above as a matter of convenience, like causes always produce like effects in like circumstances, science, and indeed all organised knowledge, would be impossible.

When fitted into our mental picture, a generalised result of experience is known as a physical law, or, to change the form of a word and the size of two letters, as a Law of Nature. Many brave things have been written, and many capital letters expended in describing the Reign of Law. The laws of Nature, however, when the mode of their discovery is analysed, are seen to be merely the most convenient way of stating the results of experience in a form suitable for future reference. The word "law" used in this connection has had an unfortunate effect. It has imparted a kind of

idea of moral obligation which bids the phenomena "obey the law," and leads to the notion that, when we have traced a law, we have discovered the ultimate cause of a series of phenomena. Newton and Ohm did not first promulgate and then enforce the regulations which are associated with their names, though it is not only elementary students who may be heard saying that a stone falls to the ground "because of the law of gravitation." We must still ask why each particle of one body attracts each particle of another, even when we know that the force between them is proportional to the product of the masses divided by the square of the distance. We do not necessarily know why the electric current through a conductor varies as the applied electro-motive force, when we have discovered how these two quantities are connected.

The great change in the rate of progress of Natural Science has occurred since men learned to concentrate their immediate attention on the question of *how* phenomena are related, and to cease, for the time at any rate, to ask *why* they appear. Before Galileo's day men sought to explain the fall of bodies to the earth by saying that "every body sought its natural place"—the place of heavy bodies being below, and that of light ones above. Galileo, exercising the true

scientific spirit of restraint, set himself to determine by experiment *how* bodies fell. He thus discovered that the speed was proportional to the time of fall, and, by dropping bodies from the top of the leaning tower of Pisa, showed that, contrary to the received doctrine of tendency to seek their natural place, heavy bodies fell no faster than light ones.

The natural laws of falling bodies were thus established, and the method of their discovery is in truth an example of the method by which such steps in knowledge are always made. The course of investigation is so regular that the process by which a physical law is discovered may well be described in general terms.

In the first stage new phenomena are observed, or old phenomena are brought under accurate and quantitative measurement. Here the virtues of patience, accuracy, incredulity, and conscientious elimination of personal bias are of chief account. The classical example of this process is Kepler's life-study of the motions of the planets.

The data accumulate; they are misinterpreted and re-interpreted, until some Newton with the touch of genius which often accompanies sober scientific insight and imagination—some one who is able to brush aside for a time the non-essential, and to rise above the confusion of detail—is inspired

with a conception of order in the multiplicity of the phenomena: order to be seen when some simple principle is borne in mind, and is expressed in a formula, which in terms of our conceptual shorthand enables us to remember and to predict the sequence of phenomena. If the formula is expressed in terms of simple conceptions, already known and often used in other branches of knowledge, the mind at once looks on it as an "explanation" of the phenomena, though it is evident on further thought that the phenomena are no more fully understood than are the fundamental conceptions—mass, force, whatever they be—in which the "explanation" is expressed.

The next step consists in deducing new consequences of the hypothesis; and here the methods of mathematical analysis are usefully applied. The science of mathematics as such has nothing to do with natural phenomena. Like physical science it is concerned with ideal conceptions; but neither does it seek to gain those conceptions from an examination of Nature, nor to check their correspondence by the methods of experiment. Mathematics may borrow subject-matter from observational science, or may acquire by pure mental processes subject-matter, such as the geometry of four dimensional space, which has no counterpart in Nature as we know it. In

either case, mathematics deals with the conceptions as such, and traces their results and the relations between them by the methods of logic, with no necessary intention of elucidating the phenomena of Nature. In his essential features, the mathematician is a calculating machine. His conclusions are, or ought to be, contained implicitly in the premises he uses. He develops the premises, discovers their full meaning, and elaborates their consequences, in a way quite beyond the unaided power of thought, which, without the guiding rules and generalisations of mathematical analysis, would be lost in the maze of complications. But the mathematician lives in a purely conceptual sphere, and mathematics is but the higher development of symbolic logic.

Taking, then, a new-born hypothesis, its consequences are deduced by logical common-sense reasoning; and, where such reasoning cannot see its way unaided, by the help of mathematical analysis. The results thus obtained are then used by the observer or experimenter, who tests by the use of old, or the determination of new data, the truth of the formula by every possible means. Its relations to other ascertained principles, its power of correlating hitherto unconnected phenomena, are examined in turn. From consideration of its significance, we gain sug-

gestions for further observation, if possible for future experiment. Such experiments, undertaken with the express purpose in view, are probably better adapted to test the formula than the blind observations previously accumulated. If the concordance is complete as far as the accuracy of experiment can go, the formula becomes, in the then state of knowledge, a "Law of Nature." Whatever this means, such a generalisation will, at all events, prove a useful working hypothesis, by the light of which research may be guided into promising paths. As the range of observation widens, and as the accuracy of the old observations is increased, the fate of the new law hangs in the balance. The formula may, perhaps, still be confirmed, it may require modification, or it may have to be abandoned as a theory which has played a useful and honourable part in its day, but has become inadequate to express the developing knowledge of a later time. If so, it ceases to be cited as a "Law of Nature." Not that Nature has changed, but rather our attitude towards her, and our conceptual model of her phenomena. Thus new laws replace the old ones.

Some years ago the constancy of the chemical elements was, in the then state of knowledge, a law of Nature. Latterly, the phenomena of radio-activity have forced us to believe that radium is passing

continuously and spontaneously into helium—that true transmutations of matter occur. The obvious transmutation of one kind of matter leads to the possibility, nay, the probability, of the gradual transmutation of all; since as yet no property of matter has been noted which is the exclusive possession of one substance alone. New phenomena, or rather phenomena for the first time appreciated, are continually coming to light, and evidence is accumulating from which the profitable construction of theories—for a time in abeyance—may again be pursued. Nothing must be ruled out of court because contrary to received views; when a *primâ facie* case has been made out, everything must be examined by experiment, induction, deduction, and again experiment. This is the only sure road to the understanding of Nature; and, in times to come, it may lead us into regions now unknown, or considered to be closed to the investigations of science. The evolution and disintegration of matter, the problems of hypnotism and of direct thought transference, are questions which seem to be rapidly coming within the range of scientific inquiry. It is possible that an advance has already been made towards clearing away part of the mystery, so attractive to some, so repellent to others, that surrounds these phenomena. At

any rate, in several of the great schools of psycho-medicine, notably in France and America, materials are being accumulated, their trustworthiness examined, and the results systematically collated. It may be that these investigations, so beset with evident difficulties, are indeed indefinitely complicated in their issues by questions of racial predisposition, of individual temperament and mental condition. Whether any or all of these problems will prove amenable to the methods of dispassionate observation and experiment is a matter which the years to come alone can show.

We must thus look on natural laws merely as convenient shorthand statements of the organised information that is at present at our disposal. But when Physical Law, as understood in the eighteenth century, has been dethroned from a place that was never rightly its own, let us not think that its usefulness has been diminished or its dignity unduly lowered. Without the possibility of framing such laws, mankind would be hopelessly lost in a wilderness of phenomena; no continuous progress could be made; no consistent idea of the world around could ever be attained. Each individual phenomenon, as it appeared time after time, might still be investigated; but, with his limited mind and short life, no one man could ever secure a basis for adequate know-

ledge. Without some general way of stating his experiences, he could hand on neither his guesses after truth nor his hard-won information : mankind would never have emerged from barbarism.

The fundamental conceptions of length, time, and mass from which, as we have seen, the other mechanical units can be derived, enable us to construct a mechanical model of Nature. It is incomplete ; for even the simplest mechanical fact, such as the fall of a body to the ground, inevitably has other aspects. Heat may be developed, electrical manifestations appear, and, if the body be a living one, physiological and psychological changes take place. Neglecting these aspects, however, a complete mechanical account of the phenomenon can be given in terms of the three fundamental conceptions. As we have seen, new ideas, which may be derived from the primary ones, become necessary in the course of the investigation. The body falls with a certain *acceleration*, and, at any instant, is moving with a definite *velocity*. As it falls, it acquires *energy of motion* and loses *energy of position*.

During the fall we find that we can successfully describe what happens by assuming that the quantity which we call the mass of the body keeps constant, and that the sum of the two kinds of

energy keeps constant also. If we include in our view the complete physical and chemical aspects of the phenomena, we may greatly extend these results. When the body reaches the earth, it is possible that processes of decay set in, which eventually result in most of its substance disappearing in gases or other products. The energy of motion acquired by the body during its fall also seems to disappear, with no corresponding gain of energy of position. Chemistry, however, generalising from many experimental results, tells us that, if we could trace all the forms of matter into which the body is resolved, we should find that there was no loss. Every particle of the original body still exists in one of its products. Physics, on the other hand, teaches us in the same way that the sum of all the forms of energy, heat, sound, &c., which appear as a consequence of the impact on the ground, could they all be taken into account, would be exactly equivalent to the energy of motion possessed by the body at the instant before contact. These great principles of the conservation of mass and the conservation of energy are two of the most important generalisations ever reached by Physical Science.

While fully recognising the importance of these generalisations from the physical point of view, we must be careful how we give them any metaphysical

significance. Under certain limiting conditions, other physical quantities besides mass and energy may be conserved. Thus in pure mechanics the conservation of momentum is well recognised, while in reversible systems thermodynamics indicates the conservation of another quantity, named by Clausius, entropy. Momentum and entropy are only conserved under restricted conditions; in physical systems the momentum of visible masses is often destroyed, while in irreversible processes entropy always tends to increase.

Mass and energy may seem to be conserved in the conditions known to us, and we are justified in extending the principle of their conservation to all cases where those conditions apply. It does not follow, however, that conditions unknown to us may not exist, in which mass and energy might disappear or come into existence. The persistence of matter, for instance, might conceivably be an apparent persistence. A wave, travelling over the surface of the sea, seems to persist. It keeps its form unchanged, and the quantity of water in it remains unaltered. We might talk about the conservation of waves, and, perhaps, in so doing, be as near the truth as when we talk of the persistence of the ultimate particles of matter. But the persistence of the wave is an apparent phenomenon. The form of the wave indeed truly persists, but the

matter in it is always changing—changing in such a way that successive portions of matter take, one after the other, an identical form. Indications are not wanting that only in some such sense as this is mass persistent. The conservation of mass and energy under all known conditions is a valid metaphysical argument in favour of the view that our ideas of them correspond with ultimate realities, but it is no more than an argument; it deserves due weight, but it is not conclusive evidence.

Even if we assume that some reality underlies phenomena, it is clear that the reality must be very different from the mental picture which common-sense frames, when unaided by the inductions of science. Our first conception of a wooden stick involves the ideas of a certain long-shaped form, of hardness, of weight, of a colour more or less brown, perhaps of some amount of elasticity. Examination with a microscope reveals many appearances invisible with the unaided eye, and we find that the stick has a structure much more detailed than we imagined. From the results of observation and experiment, physics teaches us that the properties of the stick can only satisfactorily be represented by the hypothesis that the substance of it is divisible, but not infinitely divisible; that it consists of discontinuous particles or molecules. Again, chemistry assures us that the molecules of the stick are

made up of still smaller parts or atoms, which separate from each other when chemical action occurs, when, for instance, the stick is burnt, and can afterwards re-arrange themselves into new molecules.

When we pursue our inquiries into the nature of these chemical atoms, we find that recent research has resolved them, as we shall see later, into much smaller particles or corpuscles, and we are asked to imagine that these are in constant motion within the atom, somewhat as the planets move within the solar system. Intimate relations exist between these corpuscles and the phenomena of electricity, and it seems probable that a corpuscle may be regarded as an isolated electric charge, or electron, as it is called, the mass of the corpuscle being an apparent effect due to electricity in motion.

Thus we have "explained" electricity in terms of corpuscles, and mass itself in terms of electricity. At present adventurous pioneers are striving to escape from the circle and to reach more ultimate conceptions by resolving the corpuscle or electron into a centre of intrinsic strain in the luminiferous æther. Whatever fate may await their efforts, we have already travelled far in attempting to construct a complete mental image of the wooden stick and all its known properties. We have reached ideas very different

from those of the hard, continuous substance from which we started.

The other properties of the stick can be analysed into physical conceptions in much the same way. Thus the colour is found to be due to a sorting action which the particles of the wood exert on the complex system of æthereal waves, making up white light. Some of these waves have their energy more freely absorbed by the molecules of the wood than have others; the balance of light is upset, and the reflected beam produces the sensation of colour. Here, again, the most fundamental conceptions into which modern science enables us to resolve our primitive ideas are very different from those in which they took their origin.

While Natural Science is not committed to any particular philosophical system, while in its essence it is independent of all such systems, the language it uses habitually is based on the common-sense realism, which is the philosophic creed of most men of science—indeed, of the great bulk of mankind, or at all events, of that part of mankind belonging to the races of Western Europe. The mass and energy with which we deal in physical experiments, and in the mathematical reasoning based on inductions from the experiments, are purely conceptual quantities, introduced to bring

order and simplicity into our perceptions of phenomena. But science talks of matter and energy as though it knew of the existence of realities corresponding to the mental images to which alone these names strictly apply. In the laboratory, as in practical life, there is neither room nor time for philosophic doubt. In periods of reflection, however, when considering the theoretical bearing of the results of our experiments, it is sometimes well to remember the limitation of our present certain knowledge, and the purely conceptual nature of our scheme of Natural Science when based merely on its own inductions.

# CHAPTER II

## THE LIQUEFACTION OF GASES AND THE ABSOLUTE ZERO OF TEMPERATURE

"Scientia et potentia humana in idem coincidunt, quia ignoratio causæ destituit effectum."—BACON, *Novum Organum.*

MATTER is known to us in three states—as solid, as liquid, and as gas. The relations between these three states have been the subject of investigation throughout the history of Physical Science, and, indeed, almost throughout the history of the human race. The solidification of water in a frost, and its evaporation by the sun or a fire, have been familiar to mankind from the earliest times. But water shows these changes of state under too favourable an aspect to be taken as a general example. It has by no means always been clear that such transformations were possible to all kinds of matter, and it has been necessary to exhaust the resources of modern civilisation to liquefy the more permanent gases.

Ice, when heat is supplied, begins to melt at a definite temperature, which is called 0° on the

Centigrade scale, and 32° on the scale devised by Fahrenheit. While any ice remains, no change of temperature occurs in the mixture of ice and water. Heat is still absorbed, but its energy is used to effect a change of state, not to raise the temperature. The pure substance ice has a constant melting-point. Similarly, if water be cooled at constant pressure, it begins and finishes to freeze at the same temperature. It has a constant freezing-point, identical with the melting-point.

When water boils, a still larger quantity of heat is absorbed, but the temperature again remains unaltered during the whole process. When the barometer stands at 760 millimetres, or just under 30 inches, of mercury, the temperature of the boiling-point is taken as the second fixed point on our thermometers, and called 100° or 212° according as we use the Centigrade or the Fahrenheit scale. If the barometer stands higher or lower than the standard height, the boiling-point of water is found to be above or below 100° C., rising or falling through 1° C. for a change of 27 millimetres in the barometer. The freezing-point also depends on the pressure; but the change is much smaller than in the case of the boiling-point, and delicate experiments are necessary to determine it.

The variation with pressure of the points of transition from one state of matter to another are

connected with the changes of volume which simultaneously occur. Water expands on freezing, for ice floats on the surface of a lake, and pipes burst in a frost. If this increase in volume be resisted by an external pressure, as by putting the water into a strong closed vessel, the act of freezing involves the performance of external work in forcing outwards the walls of the vessel to give room for the ice to form. It is therefore more difficult to produce ice under pressure, and a greater lowering of temperature is necessary. Thus an increase of pressure must lower the melting or freezing-point. On evaporation, the increase in volume occurs with the change from liquid to vapour; an increase of external pressure therefore makes evaporation more difficult, and consequently produces a rise in the boiling-point. If the change in volume and the amount of heat required to produce the change in state are known, the principles of thermodynamics enable us to calculate the exact amount of alteration in the freezing or boiling-points.

There is reason to suppose that the three states of solid, liquid, and gas, assumed within a moderate range of temperature and pressure by the familiar substance water, could be obtained with all bodies if we could command temperatures and

pressures high enough and low enough. Metals melt and volatilise at high temperatures, while even such gases as air and hydrogen have recently been liquefied.

Several gases, previously unknown in any other form, were liquefied by Faraday. His method consisted in evolving the gas by heating chemical re-agents in one limb of a bent glass tube, and cooling the other limb in cold water or a freezing mixture. As the gas is evolved, the pressure rises, and either the gas is liquefied in the cold limb, or the tube bursts. By this simple means chlorine, sulphur dioxide, ammonia, and a few other gases may be liquefied.

The conditions necessary for liquefaction were not fully understood till Andrews, in 1863, showed that carbonic acid gas could not be liquefied unless its temperature was reduced below a definite fixed point, which he called the critical point. The critical point of carbonic acid is fairly high, about 30° on the Centigrade scale; but for other gases, such as air or hydrogen, it is much lower, many degrees below the freezing-point of water. However low it be, unless a gas is cooled to its critical point, no pressure, whatever be its intensity, can produce liquefaction. Below their critical points, gases may be considered as vapours, and will liquefy if the pressure applied is high enough.

The problem of the liquefaction of a refractory gas is thus solved if we can produce cold sufficiently intense to reduce it below its critical point.

Three methods have been used, either singly or in conjunction, to cool gases below their critical points. The first method depends on the heat which it is necessary to supply in order to evaporate a liquid. A liquid boils when the pressure of its vapour is equal to the pressure of the atmosphere acting upon its surface, and, if we reduce this external pressure, the boiling-point is lowered. Thus, by pumping away the vapour as fast as it is formed, and so keeping the pressure low, a liquid can be boiled at a temperature much below its normal boiling-point. By this method, for example, it is possible to make water boil with no outside supply of heat. The heat necessary for evaporation is then taken from the water itself, which in this way is gradually cooled. If the air-pump is efficient, and if very little heat is allowed to leak in, the cooling may go so far that the remaining water is frozen. Beginning at the normal boiling-point of water, we should then have cooled the system by means of evaporation through 100°. If, instead of water, we had taken some liquid of low boiling-point, such as liquefied sulphur dioxide, or, better still, liquefied carbonic acid, the same process of cooling under exhaustion would have

taken place; but the final temperature reached would have been much lower.

Starting then with some substance like liquefied sulphur dioxide, which is easily liquefied by pressure alone at ordinary temperatures, we can boil it away under exhaustion, and so produce a low temperature. By making a more refractory gas, such as carbonic acid, circulate through a tube surrounded with the cooled sulphur dioxide, this new agent is cooled below its critical point, and liquefied. In its turn the liquid carbonic acid is boiled away under low pressure, and used as a refrigerating agent to cool the gas—oxygen, let us say—which we are attempting to conquer. This, sometimes called the cascade method of cooling, was the plan adopted by the Swiss physicist, Pictet of Geneva, in the experiments which, simultaneously with those of his French contemporary Cailletet, first liquefied oxygen. With one of those curious coincidences which the broad wave of advancing knowledge sometimes produces, both these results were announced at a memorable meeting of the French Academy, held on the 24th of December 1877.

Even when the gas was thus cooled, however, Pictet's process was not entirely effective. In order to pass the last few degrees and reach the critical point, a second method of cooling had to be brought into play. To explain this second method

other principles must be taken into account. When a certain mass of gas, forced into a closed vessel till the pressure rises to several atmospheres, is suddenly let out, its volume is, of course, greatly increased by the sudden expansion. Room has to be made for the increase of volume, and to do so requires the expenditure of work, for the atmosphere is pressing on the gas on all sides, and has to be forced back when the expansion occurs. Moreover, if the particles of the gas attract each other, work must be done in the separation necessary for the increase of volume. Thus internal as well as external work may be performed during the expansion. Unless heat is supplied from without, the energy needed to perform all this work must come from the heat supply of the gas itself, which becomes cooled in the process. If the expansion is sudden and therefore rapid, there is no time for heat to enter the gas, and the cooling represents the full effect of the work done. By this means, Pictet finally liquefied his oxygen. The highly compressed gas, which had been cooled in liquid carbonic acid boiling under low pressure, was allowed suddenly to escape into the atmosphere. A large amount of external work was thus done, intense cooling resulted, and liquid oxygen was seen as spray in the issuing jet of gas. It was by a still more sudden expansion that Cailletet liquefied oxygen,

using only preliminary cooling to 30° below the Centigrade zero.

In modern forms of apparatus for the liquefaction of gases it is found advisable to sacrifice the cooling gained by the performance of external work, and to rely on that due to the internal work alone. By this means it is possible to construct much more powerful and efficient refrigerating machines. The essential feature in the process of cooling by the performance of external work is the expansion of the gas by its own elastic force. If the work necessary for the increase of volume under the external pressure be supplied by an engine, or if all such work be prevented by making the gas expand into a vacuum, there is no external work to absorb the heat energy of the gas itself, and no cooling from this cause is produced. The gas, however, still has to supply any work needed to separate its own particles against any mutual attractive forces, and, if such forces exist, cooling can still be obtained at the expense of the heat-energy of the gas. On the other hand, if the inter-molecular forces are forces of repulsion, expansion will be aided by their action, and will, in the absence of external work, be accompanied by an increase of temperature. Thus, by arranging for free expansion, as it is called, we can examine the nature of the inter-molecular forces by observing whether a gas is cooled or heated.

In such experiments, it is necessary to prevent the performance of external work by the gas itself, and this can be done in either of the two ways indicated above. Gay Lussac, and afterwards Joule, filled one vessel with gas under high pressure, and then allowed it to expand into another vessel previously exhausted. Here, in expanding into a vacuum, no external pressure has to be overcome, and no external work is done. Any thermal change will be the equivalent of the internal work. The vessels were placed side by side in water, which was stirred after the experiment, and tested with a sensitive thermometer. At ordinary temperatures no heating or cooling could be observed with any of the gases examined.

The apparatus just described is clearly not adapted to detect small thermal changes, and it was not till about the year 1850, when Thomson and Joule devised a continuous method, that satisfactory results were obtained. Instead of preventing external work by allowing the gas to expand into a vacuum, these physicists performed the external work needed to expand the gas against the pressure of the atmosphere by means of an air-pump driven by an engine. By this method a continuous current of gas was forced through a porous plug of compressed wool or silk, fixed in a wooden tube. Here the engine does the external work, and con-

sequently none of that work draws on the heat energy of the gas itself.

All the external work is done by the engine, but, as we have seen, another source of energy-changes exists. When a gas expands, whether or not it performs external work, the various parts of it become separated further from each other, since, on the whole, the gas occupies after expansion a larger volume than before. If, then, there is any attraction between the parts of the gas, work must be done in separating them; in terms of the molecular theory, work is done against the inter-molecular forces. For the performance of this internal work, energy must be drawn from the heat-supply of the gas, which will therefore cool, and the amount of cooling, if access of heat from outside be prevented, measures the intensity of the inter-molecular forces. On the other hand, if the inter-molecular forces be repulsive ones, they help on the expansion, and the energy so liberated appears as sensible heat, the resultant rise of temperature depending on the strength of the repulsion between the molecules.

The porous plug experiment was originally devised by Professor William Thomson, now Lord Kelvin, and the late Dr. Joule, for the purpose of examining the amount and nature of these inter-molecular forces, and of determining the amount

of deviation of various gases from the ideal state, in which no such forces exist. If a thermometer were filled with such a hypothetical ideal gas, its indications would exactly coincide with the absolute temperature scale, deduced by Thomson from the principles of thermodynamics. The knowledge of the deviation of any real gas from the ideal state thus enables the absolute scale to be compared with the scale of an actual thermometer, using the expansion of the gas in question as the thermometric property. The great theoretical importance of the porous plug experiment will now be manifest.

Thomson and Joule found that air, and all other gases except hydrogen, were slightly cooled on passing the plug; with hydrogen, on the other hand, they obtained a still smaller heating effect. Thus in hydrogen the molecules must on the whole repel each other, while in air and similar gases, the intermolecular forces must be attractive ones. The amount of the effect was found to increase in proportion to the difference of pressure on the opposite sides of the plug.

With air the cooling effect decreases as the temperature is raised, and increases if the air be cooled. The change of temperature produced, which was only one-fifth of a degree per atmosphere difference of pressure in the original experiments, can thus be increased

to any extent by a preliminary cooling of the air.

This cooling by the performance of internal work underlies the third method adopted in the liquefaction of gases. It must be distinguished clearly from the second method, in which most of the cooling is effected by making the gas do external work.

Let us imagine that a stream of air, previously cooled by liquid carbonic acid, is forced through a spiral tube by aid of an air-pump and engine, and that finally it emerges through a fine nozzle at the end of the tube. The nozzle acts as a porous plug, and the air, cooled by free expansion, is lowered in temperature by doing internal work. Let us further suppose that the issuing air, so cooled, is made to flow back over the tube through which the stream of air passes. The advancing current of air is still further cooled, the effect of the expansion at the nozzle is increased, and a temperature yet lower than before attained. This cycle of operations—the continual passage of the air just cooled by free expansion over the current of air before it issues from the nozzle — results in a constantly decreasing temperature, and eventually cools the air below its critical point, finally causing liquefaction. This self-intensifying action is sometimes referred to as the regenerative

principle. It was first applied successfully to the liquefaction of air by Linde in Germany, and has since been used by Hampson and Dewar in England, and by Tripler in America.

Liquid air can be obtained in any quantity by the expenditure of power, and the necessary apparatus has become part of the usual equipment of physical and chemical laboratories. By this means regions of temperature before quite inaccessible have been opened up to investigation, and the use of liquid air promises to be of increasing advantage in many departments of research. It would, of course, be possible to drive an engine by means of liquid air, but such a process would be very uneconomical. The statements, which have sometimes appeared in the daily papers, announcing impending revolutions in methods of obtaining cheap power by the application of liquid air, have originated from an imperfect comprehension of the problems involved.

When air had been successfully liquefied, hydrogen was obviously the next gas to be attacked. Thomson and Joule's porous plug experiments had shown that, at ordinary temperatures, hydrogen suffers a heating effect on free expansion. It was therefore useless to attempt to liquefy it by regenerative cooling alone. But, just as the cooling effect in the case of air increases as the air

is subjected to a preliminary cooling, so in hydrogen, if it be first cooled, the Thomson-Joule heating effect first diminishes and then is reversed, becoming a cooling effect. This reversal was shown by Olszewski to take place about 80° below the Centigrade zero. Dewar then subjected hydrogen to a preliminary cooling in liquid air boiling in a vacuum at a temperature of −205°, and afterwards forced the hydrogen through a regenerative coil under a pressure of 180 atmospheres.

By this means liquid hydrogen was first collected in an open vessel on May 10, 1898, though two years before it had been seen as spray in the jet of gas issuing from a simpler apparatus of the same essential form. When about 20 cubic centimetres of liquid had been collected the later experiment failed, owing to the stoppage of the exit by frozen air, a very common accident in dealing with liquid hydrogen.

By working with carefully purified gas, much larger volumes have since been obtained, and the writer has a vivid memory of an afternoon in June 1901, when Professor Dewar had transported some five litres of liquid hydrogen from the Royal Institution to the rooms of the Royal Society, and gave his first public demonstration of its extraordinary properties. On that occasion

liquid hydrogen flowed like water, and its production in any quantity must now be regarded simply as a matter of expense.

By carefully isolating a portion of liquid hydrogen and preserving it, in a manner shortly to be described, from the access of heat from without, it was, when suddenly exhausted under an air-pump, transformed into a mass of solid frozen foam. By immersing a tube containing the liquid in this frozen foam, a small quantity of the clear transparent ice of solid hydrogen was obtained.

Kept in an open vessel, liquid air and liquid hydrogen are analogous to the water in a saucepan boiling over a fire. At the normal atmospheric pressure, water boils at 100° C., and the rate at which it evaporates depends simply on the rate at which heat enters it —depends, that is to say, on the fire below it. In a similar way, liquid air has a definite boiling-point, which, under the normal pressure of the atmosphere, rises from −192° to −182° C. as evaporation proceeds. This rise is due to the fact that nitrogen is more volatile than oxygen; and thus the liquid, as it boils away, gradually becomes richer in oxygen. Liquefied air cannot be kept in closed vessels. Its vapour pressure, equal to the pressure of the atmosphere at −190°, becomes

enormously great as heat enters and the temperature rises. In an open vessel, as heat enters evaporation proceeds, and the heat is used to effect the change of state. Thus, owing to this latent heat of evaporation which is absorbed, no rise of temperature (except the very small change already noted) occurs. But, in a closed vessel, as heat enters the pressure will rise, and the boiling-point will rise with it. The initial temperature being so low a large rise of temperature is possible, and a consequent very great increase in pressure. As ordinary temperatures were approached no vessel would withstand the internal pressure of the air.

In order to preserve liquid air for any time in an open vessel, it is clearly necessary to prevent as far as possible the access of heat. Evaporation must always be proceeding, but, by diminishing the rate at which it goes on, the loss of liquid can be considerably retarded.

Heat passes from one place to another in three ways: by conduction, when heat flows from one part of a body to another, or between two bodies in contact; by convection, when air or water, heated by contact with a hot body, rise through the colder surrounding fluid, carrying heat with them; by radiation, when heat passes directly from one body to another, as from the sun to the earth, without warming the intervening medium. Bearing

in mind these three modes of transference, Professor Dewar has invented a vessel in which a liquid gas can be kept, and the effects of all three

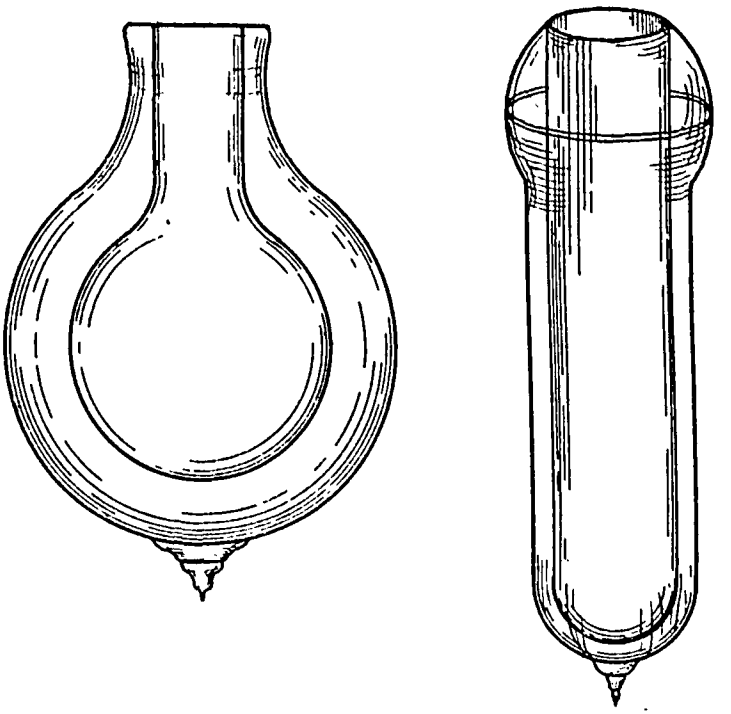


FIG. 1.

of these methods of heat-transfer be reduced to a minimum.

A double-walled glass bulb was taken, of one of the forms shown in Fig. 1, and the space between the walls exhausted of air to the completest degree possible. This arrangement diminished the effects

of conduction and convection to such an extent that liquid air, placed within, evaporated at only one-fifth of the normal rate. An additional device enabled the effects of radiation to be diminished also. A polished metallic surface is the worst radiator and the worst absorber of radiation known, and, by coating the inner wall of the vacuum vessel with a film of bright silver or mercury, the rate of evaporation of liquid air was again reduced to the sixth part. By the combined results of the vacuum and the silvering, the rate of loss of liquid was thus reduced to the thirtieth part of its value in an ordinary open vessel. Without the use of these vessels, liquid air could never be kept for any length of time, and liquid hydrogen, at any rate, could never have been collected at all.

With the liquefaction of hydrogen the old class of so-called permanent gases disappeared. In place of them, however, a number of gases, previously unknown to science, have been recently discovered. Argon, shown by Lord Rayleigh and Sir William Ramsay to exist in the atmosphere, was the first of these to be detected. Its name attempts to describe its general chemical inertness; and since this discovery several other new gases of somewhat similar chemical properties have been detected.

The story of the discovery and isolation of argon is an excellent example of the importance in science of the infinitely little, and shows how striking discoveries may be made as a consequence of experiments which seem at first sight simply adapted to investigate, with the greatest attainable accuracy, phenomena already known to science. Since the days of Cavendish, the composition of the air had been looked upon as an ascertained fact; a certain proportion had been shown to be oxygen, varying amounts of carbonic acid and aqueous vapour were known to be present, while the remainder, as the result of careful investigation, was supposed to be nitrogen. Cavendish himself knew, so accurate was his work, that any undetected residue could not exceed the $\frac{1}{120}$th part. But in the course of a long series of experiments, undertaken to determine afresh the densities of the principal gases, Lord Rayleigh detected a slight difference in the density of nitrogen as prepared from ammonia and as extracted from the air. This difference, amounting at first to about 0.1 per cent., was increased on subsequent more careful examination to nearly a half per cent. It was clear that the gases prepared by these two methods were not identical, and that some hitherto unknown body was responsible for the complication. The existence of

this new body, the inert gas now known as argon, was announced by Rayleigh and Ramsay in 1894, and shortly afterwards it was isolated from its companion.

Argon is slightly more soluble in water than nitrogen, hence a rather larger proportion of it than might be expected is found in rain water. It is also contained to a small extent in the gases liberated from certain thermal springs. Recently traces of three other gases, neon, krypton, and xenon, which much resemble argon in chemical properties, have been detected in the atmosphere. The total amount of these three substances is almost immeasurably small, and does not altogether exceed the four-hundredth part of the argon present.

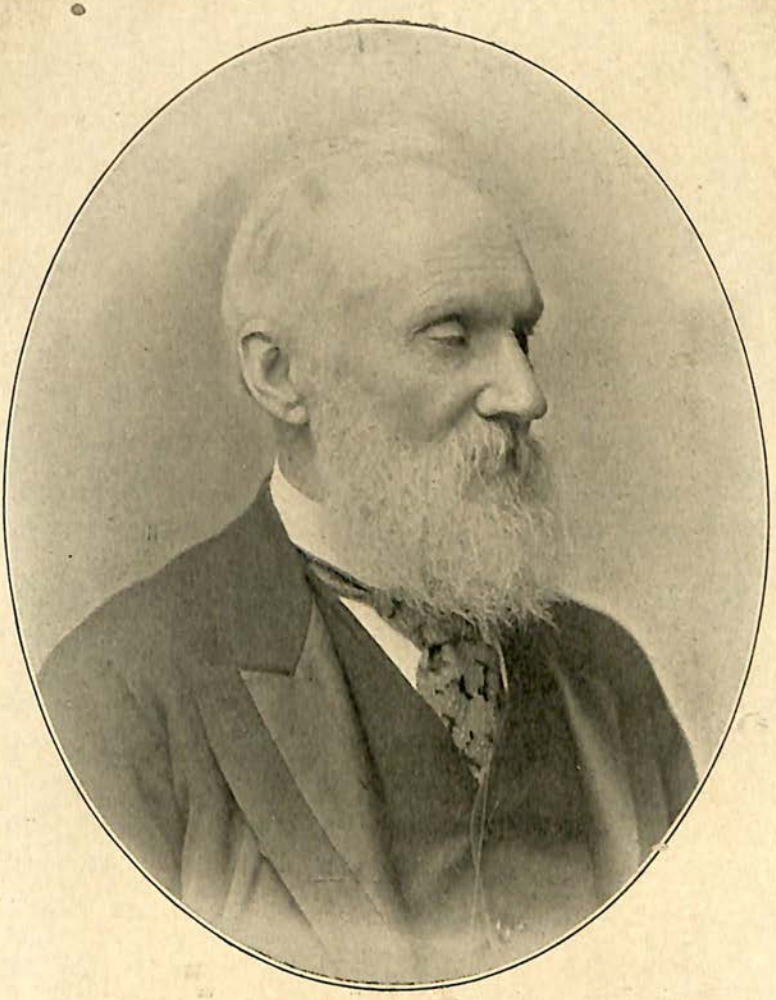
The spectrum of the sun shows lines which do not coincide with those of any chemical element under conditions usually known on the earth. Among these lines many are due to terrestrial elements in solar circumstances, but a bright line in the yellow part was detected in the spectrum of a solar prominence, and was examined carefully by Frankland and Lockyer during the eclipse of August 1868. To explain its presence they called into existence a hypothetical element, placed it in the sun, and gave to it the name helium. For many years the line in the sun's spectrum was the only evidence for the existence of helium;

but in 1895 its presence on the earth was announced by Ramsay, who had detected it in the spectroscopic analysis of the gases dissolved in the mineral clevite, together with the other new gases krypton and neon. Since this discovery, helium has been isolated and collected in appreciable quantities, and its physical and chemical properties are now well known. Helium alone, of all substances investigated, has not been liquefied. It has been expanded from a pressure of 100 atmospheres at the temperature of solid hydrogen with no signs of liquefaction, and has resisted hitherto all the refrigerating resources of the Royal Institution.

It will be seen from the foregoing account that the difficulty of obtaining these low temperatures is very great. While a temperature of many hundred degrees above the freezing-point of water is easily reached in a common fire or gas flame, to cool hydrogen to 250° below that point needs the use of powerful engines, of elaborate and costly apparatus. The difference is very marked. Moreover, it becomes more and more difficult to cool a substance through one degree as we pass down the scale. This fact suggests that there is some lower limit of temperature towards which we may strive, but with the prospect of encountering in-

creasing difficulty as we approach; it suggests, that is to say, the existence of an absolute zero of temperature.

Our knowledge of an absolute scale of temperature is due to the genius of Lord Kelvin, who, with Clausius, Rankine, and Helmholtz, may be said to have founded the modern science of thermodynamics about the year 1850. It may be shown that Lord Kelvin's absolute scale of temperature coincides with the scale of an ideal gas—a gas, that is, such as air would be if its molecules exerted no forces on each other, and, consequently, its porous plug effect were nil. As a matter of fact, at ordinary temperatures and pressures, such gases as air or hydrogen conform very nearly to these conditions—so nearly that, for all ordinary purposes, their deviations may be neglected. Now, if we keep a gas at constant pressure, its volume changes from 1 to 1.366 as it is heated from the freezing to the boiling-point of water. Similarly, if it be kept at constant volume, its pressure increases in the same ratio. If we use either of these changes as our thermometric property, and divide the interval between the freezing and boiling-points into 100° in the Centigrade manner, there will be a change in pressure, for example, of 0.00366 or $\frac{1}{273}$ of the



Kelvin
Feb 11, 1904

*Photo by Window & Grove*

*To face page* 66

pressure at 0°, for each degree through which the gas is heated. If we call the pressure at 0° unity, then at 1° the pressure will be $1+\frac{1}{273}$, at 2° it will be $1+\frac{2}{273}$, and so on. Similarly, if we cool the gas below the freezing-point, at $-1°$ the pressure becomes $1-\frac{1}{275}$, at $-2°$ the pressure is $1-\frac{1}{237}$. If, while we carry on this process, the properties of the gas remain unchanged, as they would were it the ideal gas we have supposed, at a temperature of $-273°$ the pressure will fall to $1-\frac{273}{273}$, that is, $1-1$, or zero. At $-273°$ C., therefore, the pressure of an ideal gas would vanish absolutely, and no further cooling could make it smaller. On the temperature scale which uses the pressure of an ideal gas as the thermometric property, $-273°$ C. represents an absolute zero, the lowest conceivable degree of cold. But, as we said, such a scale coincides exactly with the true absolute or thermodynamic scale, and, as can be shown, unlike all other temperature scales, is independent of the properties of any particular substance, whether real or imaginary. On the thermodynamic scale also, then, $-273°$ C. represents the absolute zero.

We thus see that the idea of an absolute zero,

at which all bodies would be entirely deprived of heat energy, is not a mere figment of the mathematical imagination, derived from the study of a hypothetical air thermometer. It has a real physical meaning, and the attainment of the absolute zero is, at all events, theoretically possible.

From the practical side, however, difficulties accumulate and increase as the absolute zero is approached. As Professor Dewar has remarked, "the step between the liquefaction of air and that of hydrogen is, thermodynamically and practically, greater than that between the liquefaction of chlorine and that of air." The boiling-points of chlorine, air, and hydrogen under the atmospheric pressure are $-33°$, $-193°$ and $-253°$ C. respectively. If we express these temperatures on the absolute scale, they become 240°, 80° and 20°. The interval between the boiling-points of chlorine and air is 160°, but the ratio of the absolute temperatures is 240 : 80, or 3 : 1. On the other hand, while the interval between air and hydrogen is only 60°, the ratio of the absolute temperatures is 80 : 20, or 4 : 1. The difficulty of the transition from one to the other temperature is much more nearly proportional to the ratio than to the difference between them.

The absolute boiling-point of hydrogen is, as we have said, about 20°, and at present this tem-

perature is the lowest at which we can continuously keep a body long enough to examine its properties. Any further advance towards the absolute zero must be made by the help of helium. By the sudden expansion of helium at a pressure of 100 atmospheres and at the temperature of solid hydrogen, it is estimated that a transient temperature of 9° or 10° absolute has been reached. Since the gas was not liquefied, the inference is that its critical point is below 9°, and its normal boiling-point about 5° absolute. This is about one-fourth that of hydrogen, and it will, therefore, be at least as hard to pass the interval between hydrogen and helium, as it was to pass that from air to hydrogen.

Nevertheless, it is likely that success is merely a matter of expense and labour. By the regenerative cooling of helium, previously cooled by liquid hydrogen boiling under diminished pressure, a temperature lower than any yet attained could be reached, and it is probable that, before the lapse of many years, the last known "permanent" gas will yield to Professor Dewar's skill and perseverance.

The liquefaction of helium will give command of a steady temperature of about 5° absolute, which is its probable boiling-point in open vessels. That temperature, within 5° of the absolute zero, is thus

almost within sight; but there, with our present methods and materials, seems to come the end of any possible advance. If, in the future, a new gas, similar to helium but of less density, should be discovered, we should find that it was still more difficult to liquefy. By using liquid helium as a means of preliminary cooling, the resistance of this hypothetical gas may possibly be overcome, and, by collecting it in open vessels under the atmospheric pressure, a steady temperature of 1° or 2° absolute may some day be placed at the disposal of the physicist.

With this forecast, the present brief historical account of low temperature research will be closed that attention may be drawn to the methods of measuring the temperatures therein obtained.

Mercury freezes at a temperature of $-40°$ C., and, at such temperatures as those now under consideration, a mercury thermometer clearly is useless. The resistance of a metallic wire to the passage of an electric current is a quantity which can be measured easily and accurately. This resistance, diminishing as the wire is cooled, depends on the temperature. With some alloys the diminution of resistance with temperature is very small, but with pure metals it is considerable, and roughly, at any rate, proportional to the change

of temperature. The metal most usually employed is platinum, since it is not attacked by acids, and is very infusible. Platinum resistance thermometers are now extensively used for physical research; they have a very large range, and are probably susceptible of greater sensitiveness than any other form of thermometer. At ordinary temperatures a difference of temperature of one ten-thousandth of a degree can be detected with moderate ease, while, with great precautions, the hundred-thousandth of a degree can be estimated. At high or low temperatures such accuracy is impossible, but measurements, correct to the nearest degree, can be made up to about 1100° C. and as low as −200° C. Below the latter temperature the rate of change of the resistance alters in a manner not yet fully investigated, and the instrument ceases to be trustworthy.

The standard to which the readings of all other thermometers are referred, as we have indicated when considering the absolute scale of temperature, is the gas thermometer containing nitrogen or hydrogen. Not only is the hydrogen thermometer thus used for purposes of reference, but it can also be employed as a practical instrument at temperatures too low to be measured by the platinum resistance thermometer. It might be thought that, as the point of lique-

faction was approached, a gas would cease to be trustworthy as a thermometric substance, but experiment has shown that, as long as the pressure of the gas is kept well below the saturation value at which condensation would occur, the gas still expands or contracts proportionally to the absolute temperature. Dewar has found that thermometers, filled with oxygen and carbonic acid at low pressures, gave correct temperatures as low as the boiling-points of those gases at the normal atmospheric pressure. He used therefore a constant volume hydrogen thermometer, working at low pressure, to determine the boiling-point of liquid hydrogen itself, and confirmed the result obtained, $-252°$ C., by experiments with a similar thermometer filled with helium.

Some very remarkable effects are obtained with liquid hydrogen. A vessel containing it is so cold that the air in contact with it immediately freezes. A snow-shower of solid air is thus produced. This process may be applied to the production of very high vacua. If the vessel to be exhausted be sealed to a long tube, one end of which is plunged into liquid hydrogen, the air in the vessel is almost completely frozen out. The air in the cooled end of the tube first condenses,

but, as it is removed, the residual air in the vessel expands, again fills the whole tube, and again that portion of it in contact with the cold part of the tube is frozen. This process continues till the pressure within the tube falls to the millionth of an atmosphere or less, a pressure so low that an electric discharge will only pass through the vessel with extreme difficulty. If, instead of air, the vessel contains some more condensible gas, such as sulphur dioxide or water vapour, the same effect can be produced by the use of liquid air as the condensing agent.

The liquefaction of air and hydrogen has enabled many experiments to be made on the influence of low temperature on chemical action, and it is found that the rate of change is very greatly affected at these temperatures. In many cases, where the reaction proceeds rapidly at ordinary temperatures, the rate is reduced to such an extent that in liquid air it becomes too small to be observed. In other cases action may cease altogether, and reagents which would otherwise undergo chemical change are maintained in false equilibrium by chemical forces analogous to those of friction. Fluorine, for instance, which attacks glass violently at ordinary temperatures, has no effect on it when cooled to $-180°$ C.

As yet, for the purposes of physical research,

a beginning only has been made in the use of the low temperatures now at our disposal. Nevertheless, Dewar, as well as Dewar and Fleming working together, have already obtained some interesting results. It is found that the elasticity of materials is greatly affected by these low temperatures. On the one hand, iron, lead, and tin, as well as ivory, showed a considerable increase in this property, balls of these substances rebounding to a much greater height than usual. On the other hand, a ball of india-rubber became brittle, and was broken by the fall. Connected with the increase in the elasticity of metals is their increased strength; wires, for example, will stand a much greater load without pulling out or breaking.

Low temperatures also affect the magnetic properties of iron, cobalt, and other metals, which are usually magnetic at ordinary temperatures, generally increasing the magnetic moment. Oxygen, slightly magnetic as a gas, as a liquid becomes strongly magnetic. The alteration of magnetic properties with temperature has been studied in detail for many years where high temperatures are concerned, and this extension of the research has been of great interest.

From the point of view of the popular lecture-room, some of the prettiest effects given by liquid

air depend on its power of imparting phosphorescence to many substances which do not usually possess this property. Ivory, egg-shells, paper, cotton-wool, and many other things glow brightly in liquid air after they have been exposed to light. On the other hand, certain sulphides of calcium, phosphorescent at ordinary temperatures, cease to be so when cooled. Some crystals, such as those of uranium nitrate, become self-luminous in liquid hydrogen, apparently owing to intense electric forces set up by the cooling. These forces may become so intense that discharges take place which are powerful enough to be visible in the dark.

It will be seen from this account that the changes in the properties of matter are more striking and complete in the range of temperature below the freezing-point of water than in the corresponding range of temperature above that point. The difference in the character and intensity of these changes emphasises the importance of the ratios of temperature as measured on the thermodynamic or absolute scale, and accounts for the greatly increased difficulty of manipulation created by every nearer approach to the absolute zero. On the other hand, it is very striking that in biological problems, more especially in those connected with

the lowliest forms of animal and vegetable life, a hundred degrees above the freezing-point is productive of a more complete and destructive change than a hundred degrees below. While exposure to the boiling-point of water, or to a temperature a few degrees higher, suffices to kill all known forms of living organisms, many forms of bacteria merely have their vitality temporarily suspended in liquid air. Even seeds of barley, peas, &c., were not permanently affected; in fact, they have recently been placed for six hours in liquid hydrogen with no effect on their subsequent power of germination.

In closing this account of low temperature research it may be of interest to tabulate some of the more important temperature-constants now known to mankind. In doing so, we cannot fail again to be struck by the high temperatures easily obtainable. On the other hand, to cool an object through 250° of the 273° which separates the freezing-point of water from the absolute zero has taxed the skill of experimenters for several generations. Temperatures, as already pointed out, are more justly compared by considering their ratio on the absolute scale than by considering the number of degrees Centigrade or Fahrenheit which separate them.

| | Temperature. | |
|---|---|---|
| | On Absolute Scale. | On Centigrade Scale. |
| Zero of the absolute scale | 0° | −273° |
| Lowest temperature yet reached | 10° | −263° |
| Boiling-point of liquid hydrogen | 20° | −253° |
| Critical-point of hydrogen | 30° | −243° |
| Boiling-point of liquid air | 81° to 91° | −192° to −182° |
| Boiling-point of liquid carbonic acid | 195° | −78° |
| Freezing-point of water | 273° | 0° |
| Boiling-point of water | 273° | 100° |
| Melting-point of tin | 505° | 231°.7 |
| Melting-point of lead | 601° | 327°.7 |
| Boiling-point of sulphur | 718° | 444°.5 |
| Melting-point of silver | 1234° | 960°.7 |
| Melting-point of gold | 1335° | 1061°.7 |
| Melting-point of copper | 1354° | 1080°.5 |
| Melting-point of platinum | 2073° | 1800° |

| | Approximate Temperature on Centigrade Scale. |
|---|---|
| Low red heat | 500° to 600° |
| White heat | 1500° to 1800° |
| Temperature of furnace | 1500° to 1600° |
| Temperature of electric arc | 3000° to 4000°. |
| Estimated temperature of the sun | 5700° to 7000° |

# CHAPTER III

## FUSION AND SOLIDIFICATION

"For more is not reserved
To man, with soul just nerved
To act to-morrow what he learns to-day:
Here work enough to watch
The Master work and catch
Hints of the proper craft, tricks of the tool's true play."
—BROWNING, *Rabbi Ben Ezra.*

IN the previous chapter we have discussed chiefly the methods employed to bring about a change of state, especially that change of state which consists in passing from the gaseous to the liquid or solid condition in the case of those substances which at ordinary temperatures and pressures exist as gases. The methods employed and the principles underlying them were the points of interest, and the whole subject belonged to that branch of physical science which consists in recognising and overcoming difficulties of manipulation, and, as it were, of asserting by force the superiority of mind over matter.

But, throughout the investigations to be pursued in the present chapter, our attitude is altered. There is no need for such attempted assertion of

supremacy. The changes of state to be examined are already under our control, and we are able to investigate further details, and probe more deeply into the intimate nature of the processes involved. We patiently seek to trace connections between, for example, the mechanical properties of metals and their microscopic structure when solidified; and, from the complicated relations which declare themselves, we may hope to throw light on the processes of fusion and solidification, and construct a theory that will hereafter prove of some use to the engineer and the metallurgist.

In the first place it is well to remark that we are seldom dealing with pure materials. Nearly the whole of the phenomena we shall consider depend on the admixture of two or more substances, one for the most part predominating. It follows that the result of the inquiry is specially applicable in all cases where traces of some impurity are the determining factor; that is, to the majority of cases, since the attainment of chemical purity is more often a pious hope than an accomplished fact.

Our investigations will lead us far afield, and we shall pass in review combinations of many of the principal metals. It is well, however, that the starting-point should be on familiar ground; if, indeed, by such a term it is permissible to indicate

the ice that occasionally covers our ponds and perpetually caps our globe.

It is well known that sea-water remains liquid at temperatures low enough to freeze ponds and lakes, and, long ago, it must have been recognised that this behaviour was due to the dissolved salt, though it was not till the year 1788 that Blagden, the first worker in the field, published a systematic series of observations on the freezing-points of salt solutions.

If we cool the solution of some substance such as sodium chloride, that is, common salt, the ice which freezes out is the solid form of pure water. The process can be illustrated in a very striking manner by using the solution of a coloured salt. If, for example, a dilute solution of the purple-coloured potassium permanganate be placed in a glass bottle and be surrounded for some hours by a freezing mixture, most of the water solidifies to form a hollow cylinder of perfectly colourless ice, while the permanganate is concentrated in an intensely coloured liquid core along the axis of the cylinder.

Similar phenomena occur in other cases where the separation is not so clearly visible.

If the ice be frozen rapidly, some trace of salt may be deposited also; but experiment has shown that

it does not enter into the composition of the crystals, and is entangled merely mechanically in their interstices. Essentially, then, the salt remains in the liquid solution, and, as the solvent is gradually frozen out, the concentration of that solution must increase. The stronger the solution becomes the lower is its freezing-point; but, if the temperature at our disposal is low enough, we can go on freezing out water till the residual solution is saturated with salt at the temperature of its freezing-point. Any further abstraction of heat, by removing some of the necessary solvent, must then be accompanied by the simultaneous deposition of salt; ice and salt will be precipitated together, and the residual solution will retain the constant composition of saturation.

Since, as the process of freezing goes on in these conditions, there is no change in the composition of the residual liquid, there can be no change in the freezing-point. The mixture of salt and water of this particular concentration will solidify completely at a constant temperature into a mixture of salt and ice of the same composition. But pure chemical elements like lead, or pure compounds like water, also fuse and solidify at constant temperatures without change of composition. In these respects, then, the particular mixture of salt and water which we

are considering behaves like a pure element or compound. For this reason Guthrie, who first systematically examined such mixtures, classed them as compounds, and named them cryohydrates. It is, however, now evident that their properties are explicable in other ways.

The phenomena we have traced, and the existence of a cryohydric point, must be borne in mind if we wish to understand the structure of natural ice, the properties of metallic alloys, or the processes which occur when, in the cold of an Arctic winter, sea-water becomes coated with a solid covering.

Natural waters, even when known as fresh, contain some amount of solids in solution. When such waters are cooled to the freezing-point, however, the crystals which appear form the ice of pure water. As the crystals grow, the dissolved salts become concentrated into the liquid which remains; and the freezing-point of this liquid falls as its concentration rises. Unless the temperature of the cryohydric point is reached, some liquid must always remain, though, with fairly pure water, it may exist only as a thin film between the solid crystals. If the temperature sink below the cryohydric point, these liquid films themselves solidify; but, even then, the mass is not a homogeneous solid, for the cryohydric conglomerate forms a

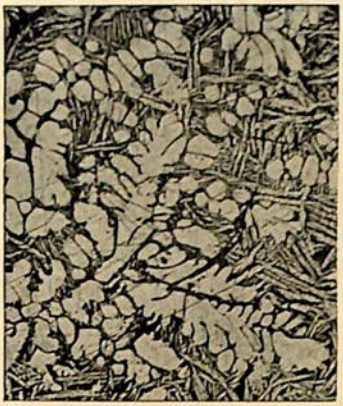


FIG. 2
Magnification 45

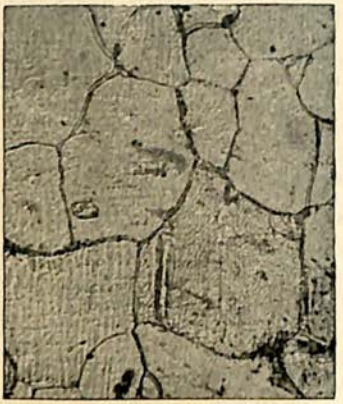


FIG. 3
Magnification 200

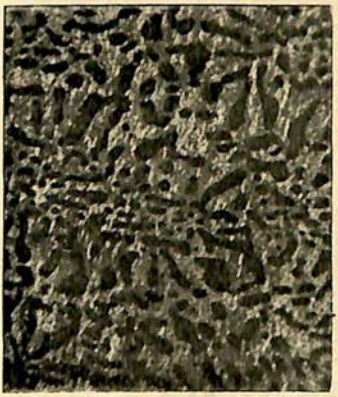


FIG. 4
Magnification 50

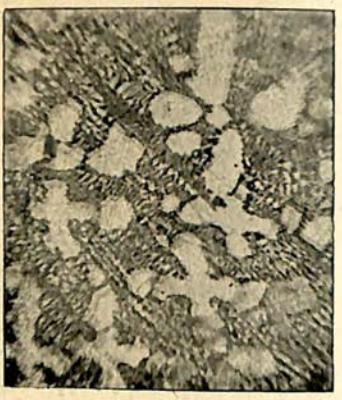


FIG. 5
Magnification 120

*To face page* 83

cement-like connection between the primary crystals of pure ice. We see now the explanation of the fact that a block of natural ice, taken from a glacier or lake, has a definite structure, and may be resolved into a heap of separate crystals by exposure to the sun. The cryohydric cement dissolves first at the lower temperature, and thus the primary crystals of pure ice fall away from each other before the temperature rises to their melting-point.

Phenomena precisely similar to those we have described appear when a fused metal is allowed to solidify. Crystalline structures of pure metal form in the liquid, and grow till the whole mass becomes solid. These primary crystals usually start as fern-like forms, of which a beautiful example is shown in Fig. 2. This represents the microscopic structure of a bronze ingot, suddenly chilled from a temperature of 644° C. If the crystals be allowed to grow by very slow cooling, they may come to fill nearly the whole mass, as in the case of the section of iron shown in Fig. 3. Even in this case, with a substance nearly as pure as can be obtained, the lines of separation between the primary crystals are clearly visible; the primary crystals are differently orientated, and their faces reflect the incident light at different angles. The

crystals of zinc are often remarkably large and well-defined, and fine specimens can be seen on surfaces of so-called galvanised iron, such as is used for water-cisterns, &c. When, instead of a single metal, traces of others are present, the lines of separation between the primary crystals are much emphasised, and, when the quantity of other substances is considerable, there arise the complicated structures, which we shall presently study under the head of alloys.

The process of the freezing of sea-water under the influence of the intense cold of an Arctic climate is an interesting example of the application of the same principles. The phenomena have been described by the explorer, Weyprecht, whose account is quoted by Mr. J. Y. Buchanan in his "Chemical and Physical Notes." When a new surface of sea-water is exposed to the cold air, in a short time the surface of the water begins to get thick, threads like a spider's web running out from the old ice. Brine is entangled in this structure, and its concentration constantly becomes greater as the quantity of ice increases. At this stage the ice is a pasty mass, and follows every motion of the water on which it floats. With a temperature of $-40°$ C. the new ice, even after twelve hours, is still so soft that, in spite of its thickness, a stick can easily be thrust through it.

As soon as a layer of ice is formed over the surface, the cooling of the underlying water proceeds much more slowly, and less salt is entangled in the crystals. The lower layers of sea-water ice give therefore, when melted, a much fresher water than can be obtained from the upper layers. Even when strong enough to walk on, the surface of new sea-ice, frozen by air at $-40°$, is still moist and soft, the residual liquid consisting of a concentrated solution of various salts, chiefly calcium chloride. The cryohydric point of calcium chloride, an extremely soluble substance, is very low, and that of a mixture of salts will be lower than that of either component. This lowering of the cryohydric temperature, which corresponds to the lowering of the freezing-point of water by the addition of salt, was observed by Buchanan in experiments conducted in the Engadine.

So far the components of the system we have been considering are not miscible with each other in all proportions; only a limited amount of salt can be dissolved in a given quantity of water A system not subject to any such restriction, in which the phenomena are as simple as possible, is found in mixtures of the metals silver and copper. The equilibrium of these substances has been studied by Mr. C. T. Heycock and Mr. F. H.

Neville, who have determined the melting-points, or rather the points of solidification, of mixtures of various proportions of the two metals. At the high temperatures involved, it would, of course, be impossible to use a mercury thermometer, and the measurements were consequently made by means of a platinum resistance thermometer, with which the temperature is determined by observing the electrical resistance of a coil of platinum wire. The metals in the required proportion are fused in a crucible and allowed to cool. As soon as solidification sets in, the rate at which the temperature falls always becomes less ; and, in the case of pure metals and other systems where the solid has the same composition as the liquid, the temperature remains constant till solidification is complete, just as the temperature of a mass of ice and water remains constant till the whole is frozen. Thus, by watching the thermometer, the temperature at which solid begins to form can be estimated.

The melting-point of silver is 960°, C. and the addition of copper lowers it just as the addition of salt lowers the freezing-point of water. This is best shown by plotting the observations on a diagram, as in Fig. 6, in which the horizontal axis denotes the composition of the mixture expressed in percentage numbers of atomic equivalents of silver and copper, and the verti-

cal axis the temperatures. On the other hand, pure copper melts at 1081°, and the admixture of silver lowers its freezing-point. The two curves in the diagram cut each other at a point which corresponds with a temperature of 777°, and a composition of 40 atomic percentages of silver and 60 of copper. At other points on the curves, the process of freezing consists in the separation of primary crystals of one or other of the pure metals

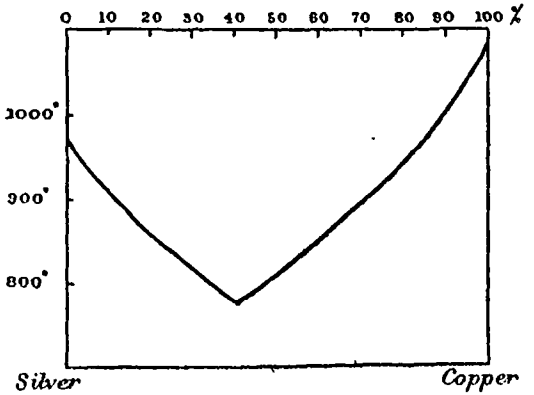



FIG. 6.

in the manner we have traced for solutions in water.* The point of intersection of the curves corresponds to the point of saturation both of silver with copper and of copper with silver.

* Osmond thinks that, in this particular case, the primary crystals are not perfectly pure. He adduces evidence to show that a slight trace of copper is dissolved in the solid crystals of silver. Any such effect, however, is hardly appreciable.

When the fused alloy has this proportion, crystals of silver and copper freeze out together, just as crystals of salt and water freeze out together when the composition of the solution is that of the cryohydrate. The point we are considering, then, corresponds with the cryohydric point for salt and water. The composition of the solid is here the same as that of the liquid, and therefore, as the process of solidification goes on, the residual liquid always has a constant concentration. Thus the freezing-point remains constant throughout the operation, and is identical with the melting-point at which liquid first appears when the solid alloy is heated. Similar phenomena constantly appear in the study of other metals; and if an alloy of this composition is polished, etched with acid, and examined under a microscope, it will be seen to consist of a uniform conglomerate of the two kinds of crystals, whereas an alloy of any other proportion exhibits larger primary crystals of that metal which is present in excess, and was frozen out first, connected by regions filled with the conglomerate referred to above. On account of its more uniform texture this conglomerate, which, as we have seen, corresponds with a so-called cryohydrate, is named the eutectic alloy. Fig. 4, on the plate facing page 83, represents a microscopic photograph of the eutectic of gold and alu-

minium; while in Fig. 5 is shown the structure of an alloy with a composition not quite that of the eutectic. Here large primary crystals have appeared, the intervals being filled with the same eutectic which is seen in Fig. 4. The metal of Fig. 4 has been cooled more slowly than that of Fig. 5, and therefore the eutectic in Fig. 4 has larger crystals and a coarser structure.

The eutectic alloy has a constant melting or freezing-point, but, during the process of fusion or solidification of other alloys, the temperature will generally change. As the primary crystals of one or other pure metal form, they leave the residual liquid richer in the other constituent, and thus with a lower freezing-point. This process continues till the liquid has the composition of the eutectic alloy, when any further loss of heat will precipitate crystals of both metals side by side. A thermometer immersed in the mixture will show the temperature at which primary crystals begin to form, and the temperature at which the composition of the residual liquid reaches that of the eutectic, for the rate at which it falls suddenly becomes much slower when solid first appears, and the fall stops altogether while the eutectic is freezing out. Thus, in such a simple case as that of silver and copper, useful information can be obtained by merely drawing the curve giving the

observed relation between the time and the temperature for the heated alloy. Such curves have forms more or less resembling that shown in Fig. 7.

With silver and copper no chemical compounds are formed; with many pairs of metals combination occurs, and the phenomena are more complicated. A definite chemical compound plays a

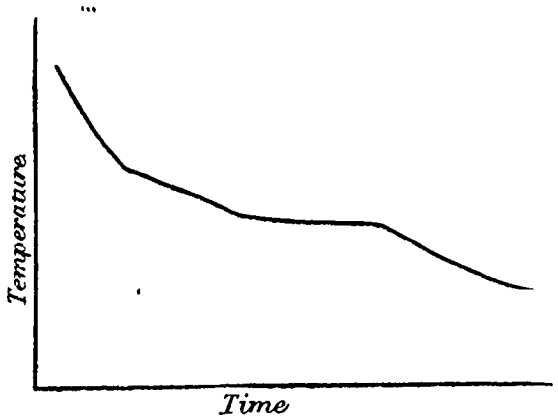



FIG. 7.

part similar to that of a pure element. Addition of either component lowers the freezing-point of the compound. Thus the point of solidification of the pure compound must correspond with a maximum point on the equilibrium curve. If a single compound is formed by the two components, the curve must consist of three branches; a branch due to the effect of the compound being interposed

between two branches similar to those in the silver-copper curve just considered. Copper and antimony form a single compound $SbCu_2$, in which two atoms of copper are united to one of antimony. The equilibrium of the solid and liquid phases has been studied by M. Le Chatelier, whose results are illustrated in Fig. 8. In this case two

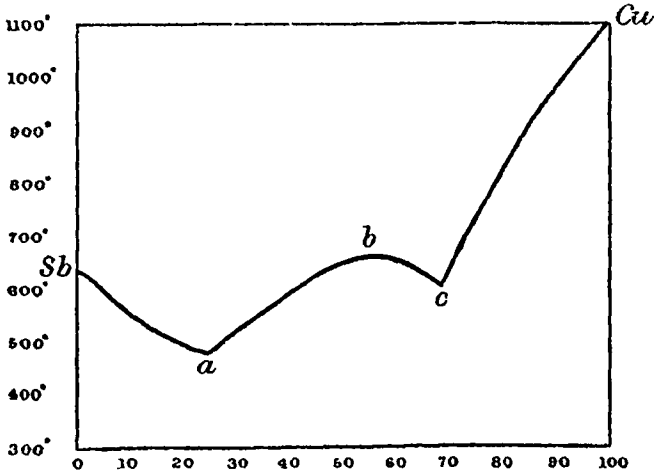
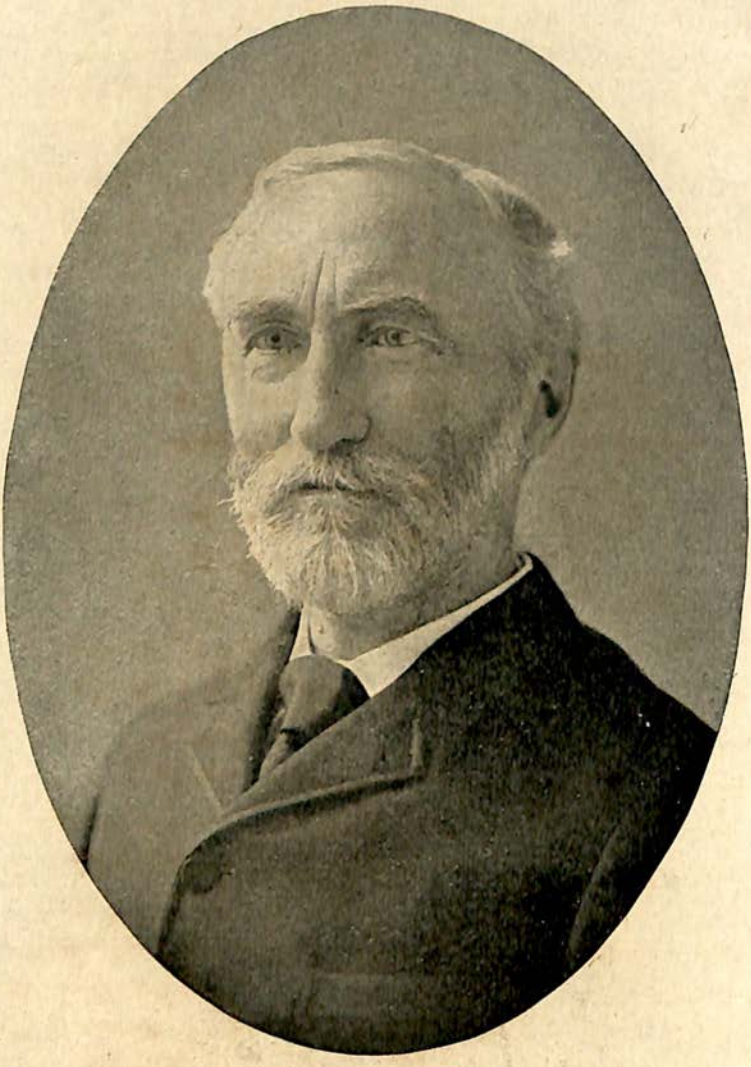



FIG. 8.

eutectic alloys are formed; one being a conglomerate of crystals of the compound with those of copper, and the other containing crystals of the compound and crystals of antimony. These eutectics are represented by the points *a* and *c* in the figure, and between them rises the curve showing the effect of the compound, which exists in the pure state at *b*, the maximum of the curve.

In all the cases yet considered, the crystals deposited consist either of a pure metal or else of a pure chemical compound. Whichever it be, the composition of any one crystalline species is fixed and definite; it does not vary continuously when the composition of the mass of alloy is altered, as does, for example, the composition of the fused liquid. In Fig. 6, page 87, the left-hand branch of the curve gives the composition of the liquid alloy which, at different temperatures, is in equilibrium with crystals of pure silver, while the right-hand branch represents the liquids in equilibrium with pure copper. One phase only, the liquid, can continuously vary in composition; the other, or solid, phase is fixed and invariable. Similarly in the case illustrated in Fig. 8, the crystals of the compound $SbCu_2$ have a fixed and constant composition. Cases are known, however, in which the solid phase also varies continuously. Many salts, such as the different alums, are of the same crystalline form, and can replace each other gradually in a crystal, which may have any composition between that of the two pure salts. Such structures are called mixed crystals or solid solutions. When they can exist, the phenomena of equilibrium become much more complicated, for the composition of the solid will vary as well as that of the liquid, and will introduce



J. Willard Gibbs

*To face page* 93

a second curve into the freezing-point diagram.

It is only of recent years that it has been possible to interpret the complicated phenomena of solid solutions. Now, however, we possess a consistent theory of the subject, founded by Professor Roozeboom of Amsterdam, on the work of the late Professor Willard Gibbs of Yale University. Long ago, in the years 1875 to 1878, Gibbs published a series of mathematical papers in the *Transactions* of the Connecticut Academy. For some time they remained practically unknown to European physicists; then they were discovered by Clerk Maxwell, who used a few of the results in his book on the "Theory of Heat." But even then the time was not ripe, and it is only of recent years that we have realised that the whole theory of chemical and physical equilibrium is contained in Gibbs' work. Buried for so long, the seed has germinated in the minds of many investigators. It has already borne good fruit, and is probably destined to bear still more in time to come. Happily, Willard Gibbs lived to see a general recognition of his genius, and the reputations made of younger men who knew how to extract and apply even single results taken from the rich store hidden in his somewhat abstruse pages.

By the use of Gibbs' thermodynamic principles,

Roozeboom was able to trace the various possible forms which could be assumed by the two curves, representing the compositions of the liquid and solid phases in equilibrium with each other. The simplest case indicated by the theory is shown in Fig. 9. In regions above the higher curve, *acb*, which is called the "liquidus," all points represent states completely liquid, while below the curve *adb*, or "solidus," the alloy is entirely solid. Between these curves exist both liquid and solid in various proportions. At a definite temperature, a liquid of one composition, say *c*, is in equilibrium with a solid of another composition, such as *d*. As the process of solidification proceeds, the composition of both liquid and solid continuously changes. In the light of these theoretical curves, the complicated experimental curves, found by observing the freezing-points of mixtures of metals and other substances, are now being rapidly interpreted in a manner which otherwise would have been quite impossible.

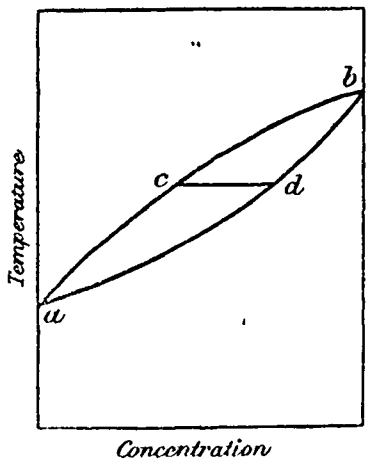



FIG. 9.

One of the most successful examples of such an interpretation is given by the very thorough study which has been made by Heycock and Neville of the bronzes, that is, of alloys consisting of copper and tin. The curves in Fig. 10 show the results of their own experiments and of previous work by Roberts-Austen. Heycock and Neville examined microscopically the structure of various alloys of the two metals in conjunction with the equilibrium curves, and have given us a knowledge of the bronzes more complete than we possess for any other series of alloys, which show phenomena of an equal degree of complexity.

Fig. 10 (p. 96) shows the equilibrium curves, from pure copper on the left to an alloy containing 80 atomic percentages of tin on the right. Above the "liquidus" ABCDEFGH the alloys consist of a homogeneous liquid, in which solid first begins to form when the temperature falls to points represented on the curve. The "solidus" curve, below which the whole mass is solid, is the complicated curve A*blcmef*$E_2E_4H''M$.

It has long been known that the physical properties of metals, especially of alloys, depend on the way in which they are cooled from a state of fusion. The whole process of the annealing or tempering of steel depends on a perception of this fact. Many observers have studied the changes of

physical properties thus produced by examining microscopically the solid alloys obtained by different treatments, and relations between the properties of the alloy and its microscopic structure had been traced. But for the first time a complete investigation has been made by Heycock and

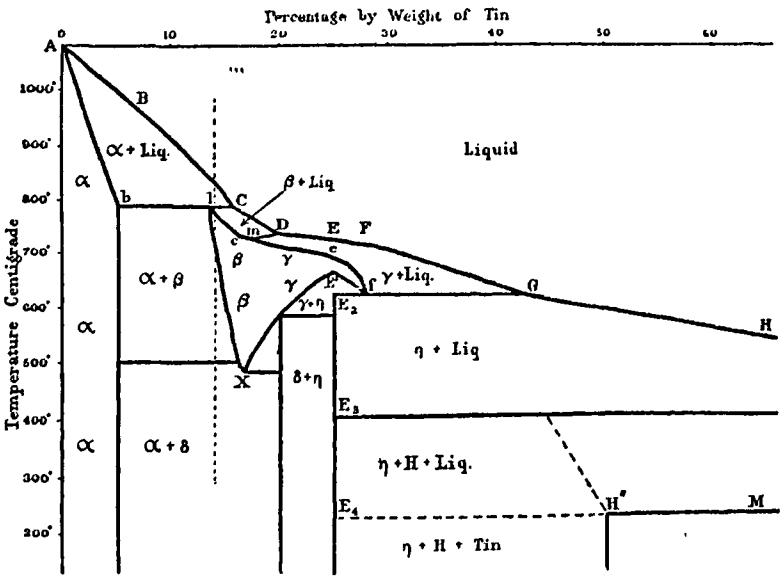



FIG. 10.

Neville of the changes in microscopic structure produced by different methods of cooling, and studied in conjunction with the equilibrium curves by the light of the theory of solid solutions. The work was rendered possible by the fact that, if a hot metal be suddenly cooled from any tempera-

ture by chilling it in cold water, the microscopic structure it possessed at that temperature is almost perfectly stereotyped by the process of sudden chilling, and can be examined at leisure in the cold metal by polishing and etching it in the usual manner.

In this way have been detected and traced equilibrium curves lying below the solidus. Such curves represent changes of structure which occur in a mass completely solid, and quite explain the changes in physical properties caused by annealing or chilling. Take as an example the two curves *l*X and E′X, which cut each other in the point X, and recall in their general form and relations the simple curves of equilibrium between liquid and solid for alloys of silver and copper already described and illustrated in Fig. 6 (p. 87). The analogy is more than one of mere form. Just as crystals of silver or copper separate out of the homogeneous liquid of Fig. 6, so crystals of new substances separate out of the homogeneous solid solution which exists within the triangular space *l*X*fl* in Fig. 10; and, as the crystals of silver or copper are in equilibrium with the liquid alloy in states represented by points on the freezing-point curves of Fig. 6, so the new crystalline structures are in equilibrium with the homogeneous mother substance lying within our present triangle.

The positions of these curves of equilibrium between solid phases are investigated chiefly by the microscopic examination of ingots of metal, which are fused, allowed to cool very slowly to the temperature to be investigated, in order that, as far as possible, equilibrium may be reached, and then suddenly chilled by immersion in cold water. A section of the ingot is polished and etched with acid or other suitable liquid, in order to bring out the structure-pattern. Each pure metal, compound, or solid solution, crystallising from the mother liquid, possesses a characteristic appearance, which can readily be recognised after some practice in interpretation of the micro-photographs. Such photographs enable us to trace the formation, development, and decay of new crystal-species in a liquid or in a solid matrix.

The effect on the microscopic structure of differences in the rate of cooling is well shown in Figs. 11, 12, and 13. The same alloy is represented in all these photographs, and is, in each case, chilled from about the same temperature. The differences in structure depend solely on the differences in the rate of cooling from a liquid condition to the temperature at which the ingot was chilled in cold water.

The alloy contained 13.5 atomic percentages of tin, and is represented by the vertical dotted line

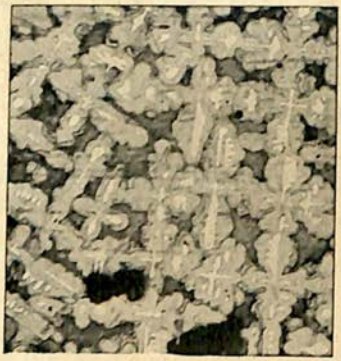


FIG. 11.—Magnification 18

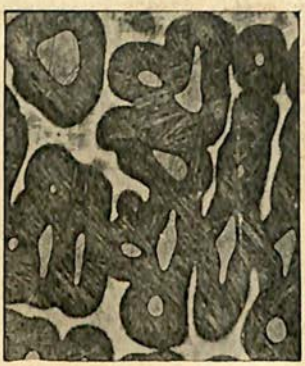


FIG. 12.—Magnification 45



FIG. 13.—Magnification 18

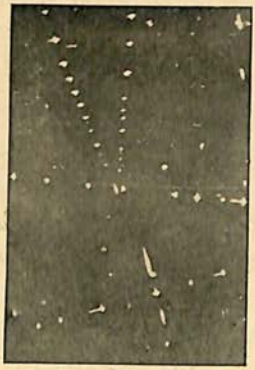


FIG. 14.—Magnification 18



FIG. 15.—Magnification 18

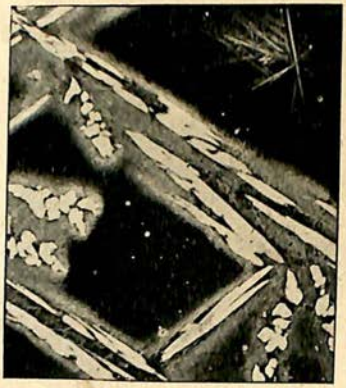


FIG. 16.—Magnification 18



FIG 17.—Magnification 18

*To face page* 99

in Fig. 9. When this alloy in cooling passes the liquidus ABC, crystal skeletons of a solid solution called $\alpha$ appear mixed with the mother liquid. These skeletons somewhat resemble the larger fern-like structures of Fig. 2 on page 83, which, however, chosen chiefly for its beauty, was taken from a bronze of another composition.

When the alloy we are now considering passes the line *l*C (Fig. 10), a new kind of crystalline solid solution, called $\beta$, begins to form ; and, if time is given it by keeping the ingot hot, the $\beta$ substance gradually eats up the existing crystals of $\alpha$. This process is illustrated in Figs. 11, 12, and 13. In Fig. 11 the residual $\alpha$ is seen as white cores within the grey $\beta$, which follows the arrangement of the original $\alpha$ structures, while, in the particular illumination employed, the part that was liquid at the instant of chilling shows as a dark background. In Fig. 12, where the ingot was cooled more slowly, the change has gone farther ; the $\beta$ substance ceases to follow the original skeletons of $\alpha$, a higher magnification brings out the characteristic striated appearance of the $\beta$, while, owing to a different illumination, the mother liquid shows as a light background. Fig. 13 is taken from an ingot which had been cooled to the same chill point exceedingly slowly, and kept many hours just above that temperature. The whole ingot is now

filled with uniform striated $\beta$, a tiny speck of $\alpha$, seen towards the lower side of the photograph, alone remaining. In the light of these three photographs it is not surprising that the physical and mechanical properties of metals are profoundly modified by differences in the rates at which they have been cooled from a fused condition.

Following the dotted line in Fig. 9 still further, we see that, in ingots chilled from temperatures about 750°, $\beta$ alone should exist. Fig. 14 shows a chill from 740°, which was cooled to that temperature almost slowly enough to destroy all the primary crystals of $\alpha$, which now only show as scattered specks of white.

Again following the dotted line in the equilibrium curve of Fig. 10, we pass the boundary IX, and again enter a region where $\alpha$ and $\beta$ exist together. The facts on which this curve is based are illustrated in Fig. 15. Here a new or secondary crop of $\alpha$ crystals has begun to grow. This ingot was chilled at 558°, and there is no doubt that the new growth of $\alpha$ took place in a mass which had long before completely solidified.

The further growth of the new $\alpha$ is seen in Fig. 16, which represents an alloy of slightly higher content of tin (14 atomic per cents) chilled from a temperature of 530°. As the alloy in cooling passes the temperature of 500°, the whole

of the $\beta$ substance is transformed into a complex consisting of $\alpha$ crystals intimately mixed with a new solid solution called $\delta$. This complex is shown in Fig. 17 as a light background; while, in contrast with it, the $\alpha$ crystals come out dark after the treatment adopted.

These changes again occur in a mass thoroughly solid throughout, and explain in a most striking manner the effect of such processes as annealing and tempering, in which the properties of metals are altered by heating them to a temperature well below their fusion point and then cooling them either slowly or rapidly.

Heycock and Neville's investigation of the bronzes was a very laborious undertaking. One hundred micro-photographs were published, and these represent only a selection of those taken; many observations of freezing-points were also made. But the labour of the work is well repaid by the magnificent results finally obtained.

Iron and steel, as used in the arts and industries, consist of pure iron alloyed with various substances, chiefly carbon. Solid solutions, similar to those we have studied in other cases, are formed between iron and carbon, and the phenomena of equilibrium between the liquid and solid phases,

even when no other component is present, are very complicated.

Owing to their industrial importance, the alloys of iron have been investigated more extensively than those of any other metal, and the various compounds and solid solutions identified have received definite names, which, in many cases, were given long before the application by Roozeboom of the theory of solid solutions enabled the true phenomena of equilibrium to be understood. Roozeboom's diagram for alloys of iron and carbon, containing less than 7 per cent. of carbon, is reproduced in Fig. 18. Its general meaning will be clear in the light of what has been said in the case of the bronzes. Here again changes occur at definite temperatures, even in alloys which are completely solid. The viscosity of the material makes these changes very slow, and very different proportions of the various possible constituents will be found in alloys that have been cooled quickly and slowly. The effects of tempering steel and iron thus receive a physical explanation.

By heating iron above one of the transformation temperatures indicated in the diagram, and maintaining it at a high temperature for some time, it will obviously be possible to produce extensive changes in the physical nature of the metal,

Recent work by Mr. J. E. Stead has shown, that when steel rails have become dangerously brittle and crystalline by long use, they can be reconverted into a tough, elastic, and therefore safe

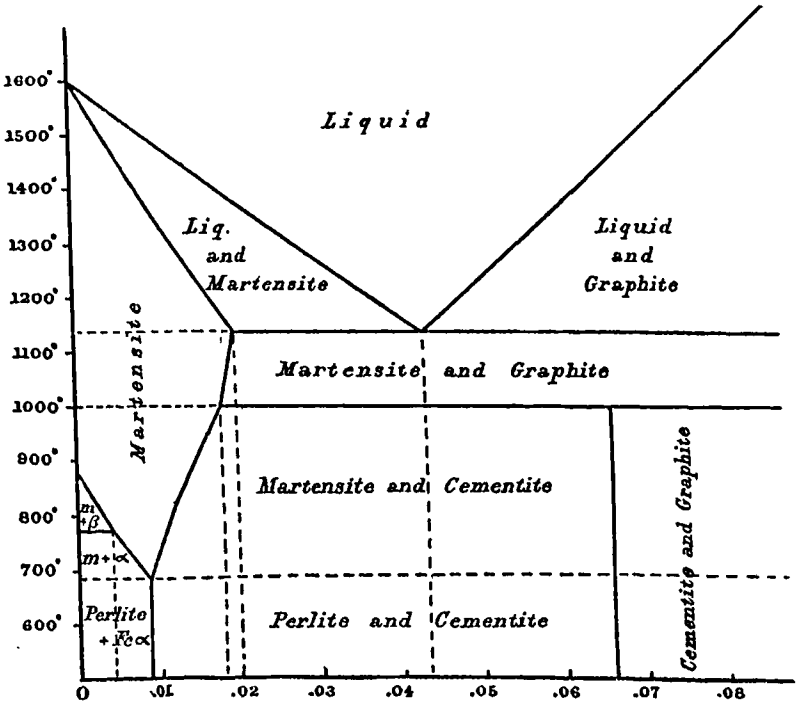



FIG. 18.

condition by prolonged heating at temperatures from 850° to 900° C. This improvement in properties has been traced to the development of a constituent of the alloy known as sorbite. It is this constituent which gives the peculiar tenacious

properties to iron which has been specially prepared for drawing into wire.

Microscopic studies of the alloys composing iron and steel have been very numerous. The work of Sorby, Andrews, Osmond, Le Chatelier, and Stead should particularly be mentioned. It is by such microscopic investigations that the different constituents of the alloys have been for the most part distinguished, the crystals of each constituent having a characteristic appearance, which usually persists throughout a series of changes.

The investigations we have described all emphasise one point—the fact that metals possess a structure essentially crystalline. In some cases, such as that of the surfaces of zinc deposited on so-called galvanised iron, this crystalline structure is readily visible, but most of the metallic objects in common use possess polished surfaces on which no trace of crystals can be seen. The possibility of polishing a surface to such a state of perfection that it will act as a mirror and reflect a ray of light without appreciable scattering, is a matter of considerable interest. Any irregularities on such a surface must be small compared with the wavelengths of light, and it is difficult to see how any such surface could be obtained by the use of ordinary polishing materials, if the action of these



FIG. 19.—Magnification 775



FIG. 20.—Magnification 775



FIG. 21—Magnification 775

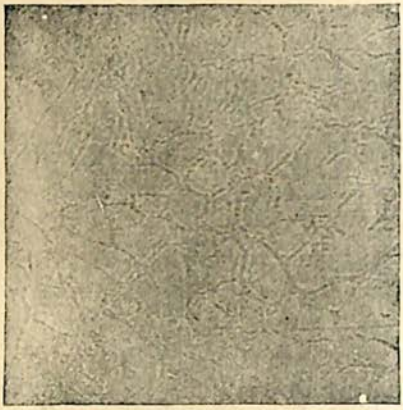


FIG. 22.—Magnification 775



FIG. 23.—Magnification 775

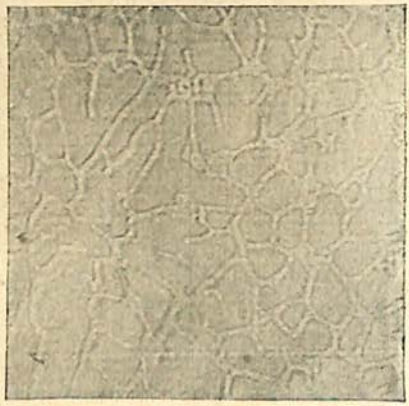


FIG. 24.—Magnification 775

*To face page* 105

materials be regarded as a mere mechanical grinding away of projections after the manner of a file.

Many careful observations have been made on the process of polishing. The latest of these observations were published in August 1903 in the "Proceedings of the Royal Society." Mr. G. T. Beilby has investigated the subject microscopically, and finds reason to believe that the passage over the surface of a scratched metal of a polishing substance like wash leather covered with rouge produces a kind of surface flow, the outer layers of the metal flowing like a viscous liquid under the action of the pressure on the polishing tool, and assuming an optically perfect surface under the influence of surface tension. In this way a film is formed over the surface of a metal, which film is in a state essentially different from that of the bulk of the substance below. Inside the metal the crystalline forces have full play ; at its surface, the controlling influences consist in part of surface tension, which, under the pressure of a polishing tool, is able to overcome the tendency to assume a crystalline structure. Figs. 19 to 24 show six of Mr. Beilby's photographs. Fig. 19 shows the surface of crystalline antimony after rubbing with fine emery paper. The magnification is such that the photograph is 775 times life-size. Fig. 20,

which represents the same surface after polishing with rouged leather, shows the gradual dragging of a film of metal over the pits and furrows of the first surface. The larger pits get filled with filings of metal, and the film seems to bridge them over, forming a continuous sheet over the loosely-packed fragments below. When an acid or other liquid capable of dissolving the metal is placed on the surface, the film is dissolved, and the pits and furrows reappear. This comes out in Fig. 21, in which the antimony previously polished has been etched with a solution of potassium cyanide. Fig. 22 shows a polished surface of speculum metal, an alloy used for the reflectors of telescopes. Here the underlying crystalline structure is faintly visible. The surface film has, in Fig. 23, been removed with potassium cyanide, and the structure is now plain, the primary crystals, separated by channels of eutectic alloy, being clearly brought out. Finally, in Fig. 24, the same surface has been repolished, and the channels bridged over with the flowing film of viscous metal.

These experiments have an interest which extends further than the immediate subject to elucidate which they were undertaken—an experience not uncommon in physical research. The existence of this viscous metallic film under

certain conditions suggests that, when minute quantities of a solid alone exist—when there is in effect inside the surface film no substance beyond the range of molecular action—all crystalline structure must disappear. The initial formation of solid in the body of a saturated solution or of a fused material will, on this view, be exactly co-ordinated with the deposition of drops of water from a mass of air saturated with aqueous vapour, and the possibility of super-saturation will, in each case, depend on the work required to form a new surface of separation under the influence of surface tension alone. It is only when the individual solid structures attain a considerable size that crystalline forms begin to appear.

# CHAPTER IV

## THE PROBLEMS OF SOLUTION

"If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also . . . is divided into definite elementary portions, which behave like atoms of electricity."—H. VON HELMHOLTZ, "Faraday Lecture," 1881.

To one inexperienced in the problems which confront the workers in the world of natural science, the whole question of solution and its attendant phenomena may appear, at first sight, of small account. Yet the study of these same phenomena, and the unravelling of their intricate connections, are of fundamental importance. Furthermore, as the work of the last twenty years has shown, the problems involved are of increasing interest, not only from the point of view of physics and chemistry, but also, and perhaps especially, from the physiological standpoint. More and more the reactions of inorganic substances, whether liquid or solid, are referred to their properties in a state of solution, while every process of life to be investigated by the biologist seems capable of interpretation only

through attention to the conditions thereby involved. Moreover, most chemical actions, especially those easily examined in the laboratory, occur between substances one or more of which are actually in the liquid state; while the application of physical conceptions to the problems of living matter chiefly depends on the knowledge we possess of the physics and chemistry of ordinary solutions.

The earliest investigations of the subject were of a chemical nature, and, till the passage of electric currents through liquids came to be examined at the beginning of the nineteenth century, little systematic study of the physical properties of solutions was made. But since that period there has been constant progress, and many new fields of research have been opened up.

It constantly happens that light is thrown on the dark places of one science by work undertaken to elucidate those of another; and, in this case, the starting-point for the modern theory of solution is found in some experiments made by Pfeffer in 1877 in a botanical laboratory. Ten years earlier, Traube, in studying the modes of formation of the organic cells of plants and animals, had discovered how to construct artificial membranes permeable to water but not to solu-

tions of certain substances dissolved therein. Pfeffer made a further examination of these semi-permeable membranes, as they have been called, and by their use obtained results of great importance in the study of biology.

A porous pot of unglazed earthenware, six to eight centimetres high and two or three centimetres in diameter, is sealed by means of sealing-wax to a glass tube, as shown in Fig. 25. Having been thoroughly washed, it is filled with the solution of a salt, such as potassium ferro-cyanide, and the outside is then surrounded with the solution of another salt, such as copper sulphate or ferric chloride, which gives an insoluble precipitate when in contact with the first salt. The two solutions gradually diffuse from opposite sides into the walls of the cell, and form an insoluble membrane where they meet inside the thickness of the walls. This process can be hastened, and the resulting membrane improved, by forcing the salts into the porous material by means of an electric current. The solutions are washed away, and the wide glass tube is drawn out and sealed to a smaller tube in the manner shown in the figure.

Inside a cell thus prepared let us place the solution of some substance, such as sugar in water, and surround the outside with a large volume of

the pure solvent, in this case, water. Water will

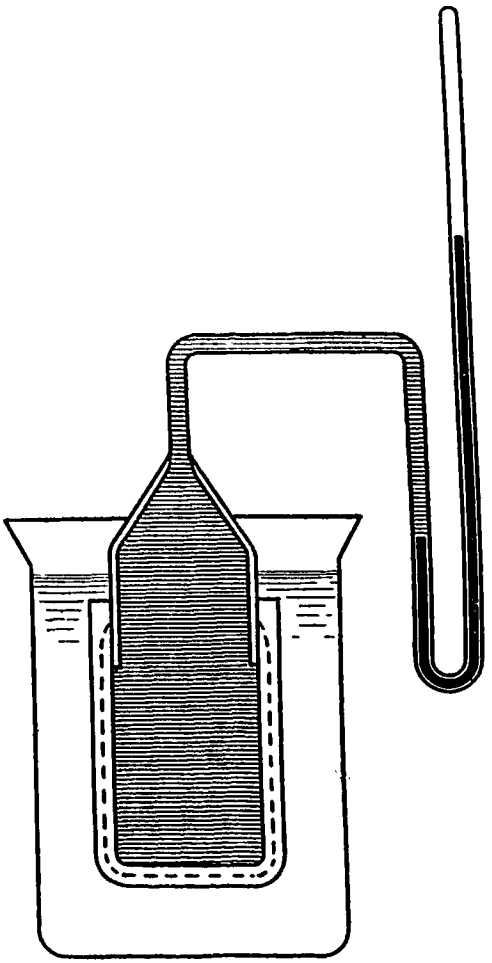


FIG. 25.

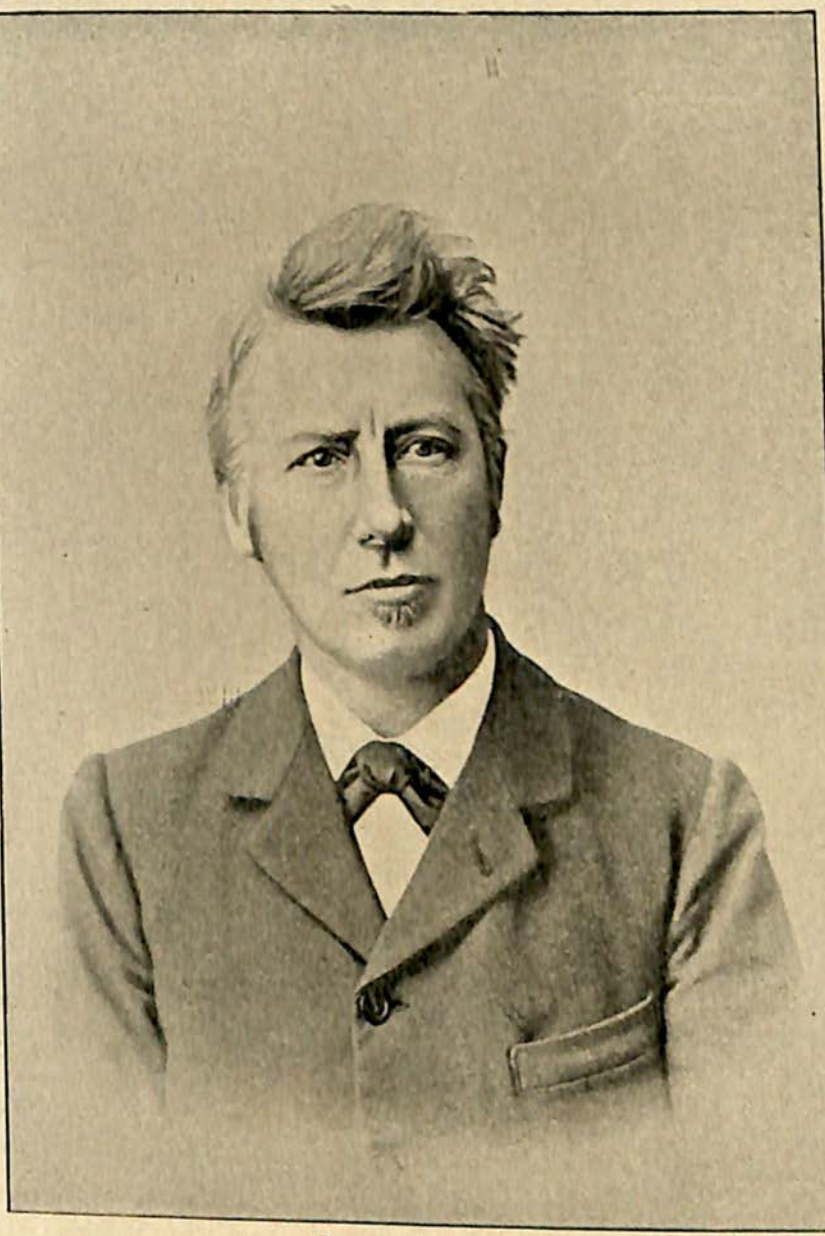
gradually force its way into the cell, and, by placing mercury in the glass tube to use as a pres-

sure gauge, it will be found that this influx will continue till a definite internal pressure is reached. This gives a measure of what is called the osmotic pressure of the solution as it finally exists in the cell after the entrance of the additional quantity of water.

Pfeffer found that this osmotic pressure was proportional to the concentration of the solution, at all events between the concentrations of 1 to 6 per cent. of sugar. For a 1 per cent. solution, the pressure at 6°.8 C. was equal to that of a column of mercury 505 millimetres high, the normal atmospheric pressure being equivalent to 760 millimetres.

Many membranes within animal and vegetable organisms are semi-permeable, or, at all events, are more permeable to solvent than to solution. The permanent or temporary differences of pressure, which are thus set up, are being extensively investigated by physiologists, and have already been shown to play important parts in the processes of living structures.

Attention was first called to the interest and importance of osmotic pressure from a physical standpoint by the distinguished Dutch chemist, Van't Hoff, who is now Professor at Berlin. In 1885 Van't Hoff pointed out that Pfeffer's numbers showed: (1) that the osmotic pressure



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was inversely proportional to the volume in which a given mass of sugar was confined; and (2) that the absolute value of the pressure in the case of the solution of sugar was the same as that which would be exerted by an equal number of molecules of a gas when placed in a vessel having a volume equal to that of the solution. For instance, a quantity of gas of the same molecular concentration as a 1 per cent. solution of sugar would, at 6°.8 C., exert a pressure equivalent to that of 508 millimetres of mercury, a number identical within the limits of experimental error, with Pfeffer's observed value for the osmotic pressure. The first result is equivalent to the extension to dilute solutions of Boyle's law for gases, a law which states the experimental result that the volume of a gas is inversely proportional to its pressure. The second result shows that, in a dilute solution, the pressure depends only on the number of molecules present, and not on their nature—a statement which, applied to gases, is known as Avogadro's law.

But Van't Hoff did not alone call attention to the experimental basis of the new subject. He also placed the theory of it on a sound footing. The amount of a gas which dissolves in a given quantity of water is proportional to the pressure, and from this experimental result Van't Hoff

showed mathematically by the principles of thermodynamics, that, when in solution, this same gas must exert an osmotic pressure of the observed value. The proof involves no assumptions as to the physical mechanism by which the osmotic pressure is produced. Whether it be due to the impacts of the dissolved molecules on the semi-permeable walls, in the same way that the molecules of a gas exert pressure on the walls of the containing vessel; whether it be due to chemical affinity between the dissolved substance and the solvent, affinity which causes more solvent to enter the cell; or whether some other hitherto untraced effects come into play, remains an open question. The thermodynamic argument simply shows that, from the experimental solubility relations of gases, the observed osmotic results follow for the gases when dissolved; but the physical *modus operandi* of the pressure remains uncertain.

The extension of the theoretical result to the case of non-gaseous solutes like sugar involves a certain amount of assumption. However, since substances of all degrees of volatility are known, the extension seems reasonable; and it is abundantly justified by Pfeffer's experimental measurements.

Another method of applying the principles of

thermodynamics to this problem has been developed by Willard Gibbs, Von Helmholtz, and Larmor. Whatever view we take of the fundamental nature of a solution, we must imagine the dissolved substance scattered as a number of discrete particles throughout the volume of the solvent. The nature of the interaction which occurs between the solute and the solvent is unknown, possibly unknowable; but, whatever it may be, each particle of solute will affect only a minute sphere of solvent lying round it. The solution, then, may be regarded as containing a number of little systems, each composed of a solute particle surrounded by an atmosphere of solvent in some way influenced by its nucleus.

While the solution is concentrated, the little spheres will intersect each other, and the addition of further solvent will involve some change in the interaction between solute and solvent. But, in the process of dilution, a time will come when the spheres are beyond each other's reach, and the addition of more solvent merely increases their mutual separation without affecting their internal structure.

Thus, in a dilute solution, the energy-change of further dilution is merely the energy-change involved in separating the particles of the solute; it will not depend on the nature of any possible

interaction between the solute and the solvent. The change of energy is thus independent of the nature of the solvent, and will be the same whether that solvent be water, alcohol, or any other liquid. It will even be the same when, in cases where it is possible, the solvent is removed altogether, and the solute is obtained in the gaseous state.

If we imagine that the bottom of a frictionless engine cylinder is made of a semi-permeable membrane, separating a solution within the cylinder from a solvent without, it is easy to see that osmotic pressure may be made to do work, which will be measured by the pressure multiplied by the change of volume. Thus the osmotic pressure is measured by the change of the available energy per unit increase of volume; that is, by the rate of change in the available energy of dilution.

In this manner we again arrive at the conclusion, that the osmotic pressure must be equal in amount to the gaseous pressure exerted by the same number of molecules when vaporised, and must conform to the laws which describe the temperature, pressure, and volume relations of gaseous matter. The result is clearly seen to be independent of any hypothesis concerning the mechanism of the pressure or the nature of the solution.

In the last chapter we have traced the phenomena of fusion and solidification, and, in the course of our inquiry, studied the equilibrium of liquid solutions with the different solid phases which may exist in contact with the liquids. The fundamental problem of the nature of a solution was untouched; indeed, from the point of view then adopted, such a problem did not arise.

Until the last quarter of the nineteenth century, it was generally assumed that the forces which were brought into play when a solid dissolved in water were of the same nature as those involved in chemical action; and the resulting solution was looked on simply as a chemical compound in which there happened to be no fixed relation between the masses of the components. The study of dilute solutions, and, in particular, the examination of their osmotic pressures, showed that, in many respects, a dilute solution was analogous to a gas, and conformed with the same laws relating to the pressure, volume, and temperature. Such results emphasised the analogy between the dissolution of a solid and the diffusion of a gas through a space in which it was not originally present, and sometimes led to the idea that the osmotic pressure of a solution, like the pressure of a gas, was due to the impact of its molecules on the containing wall. As an extreme case of this aspect of the

phenomena, the view has been expressed that the solvent should simply be regarded as giving room for the diffusion of the molecules of the solid; any possible interaction, of a chemical nature or otherwise, between the solvent and solute being disregarded.

The similarity between the laws of gases and those of dilute solutions, however, does not necessarily connote identity in physical nature; the account of the subject given by thermodynamics clearly shows that the essential feature, common to both cases, on which the similarity depends, is the dilution. In a gas the molecules are, on the average, too far from each other to exert appreciable intermolecular forces, and the change in energy produced by further dilution does not involve such intermolecular forces. In the same way the dissolved molecules in a dilute solution are so far from each other that, whatever be their action on the solvent, they exert none on each other. Here again, the change of energy on further dilution does not involve the forces between those molecules which alone from this point of view are to be considered, that is, the molecules of the dissolved substance. The essential point is the distant separation of the molecules in each case from each other; any interaction between solvent and solute would not affect the result, and the result therefore

cannot be used as evidence for or against such interaction.

The similarity in pressure-volume laws, then, cannot be regarded as determining the question whether solution is, in its essential nature, chemical or physical. To settle such a problem other evidence must be sought. Very little such evidence is yet available; what little there is seems rather to favour the chemical view, which regards a solution, say of salt and water, as in some way a chemical compound of these components; a compound in which the relative proportion between the components can vary continuously between certain wide limits.

The results in this case are characteristic of the methods of thermodynamic theory as applied in physical science. Thermodynamics is not concerned with the physical *modus operandi* of the phenomena. It does not involve molecular hypotheses; it is free from any doubt which accompanies such hypotheses, though it gives less insight into the intimate processes of the phenomena than do successful molecular conceptions.

In the development of several branches of physics and chemistry two stages can be traced. It has sometimes happened that the earliest theoretical account of a subject has been given from the mechanical or molecular standpoint. In

this way a definite working hypothesis has arisen, on the lines of which much investigation has been undertaken. Gradually, however, this preliminary scaffolding has been found to be unnecessary, and a thermodynamic theory has been developed, which directly connects the phenomena, and brings out their relations with similar phenomena in other branches of science.

The two methods may perhaps be illustrated in some such way as the following. In looking at the face of a watch, certain relations are observed between the positions of the two hands at different times. In order to explain these phenomena we make hypotheses concerning the structure of the inside of the watch. We imagine various arrangements of springs, wheels, and levers till we hit on one particular system which consideration shows us will give the observed result. Here we have an intimate picture of the inside of the watch, which may or may not represent the only possible arrangement, and may or may not correspond with the reality. Such a picture is analogous to a molecular theory of a physical problem.

One day, however, we notice, in the course of our studies of the watch, that, whatever be the position of the hands, one of them always moves sixty times as fast as the other. We have discovered a necessary relation between the

phenomena, which enables us, if we will, to dispense with all hypotheses about the wheels and springs which drive the mechanism. The observed connection between the rates of motion allows us to evade all such complications, and to calculate directly the relative positions of the two hands at any future time.

So with thermodynamics. Lord Kelvin's great principle of the dissipation of energy, especially in its modern form, which states that the available energy of an isothermal system tends constantly to decrease, enables us in many cases to evade all molecular considerations, and to trace directly the relations between various physical and chemical phenomena. By this method it is possible to develop the theoretical relations of many subjects without involving the molecular hypothesis. Such treatment, using as its sole principle of co-ordination the law of available energy, ultimately rests on the experimental impossibility of perpetual motion.

This way of treating physical science has recently been adopted by a certain number of chemists, as a means of presenting their subject without applying to it the language or conceptions of the atomic theory, in terms of which even its simplest experimental facts have come to be expressed. In particular Franz Wald and Ostwald have explained the phenomena of chemical com-

bination in definite proportions from the standpoint of energetics. They have shown that the existence of the two types known to us as elements and compounds may be deduced from the thermodynamic theory of equilibrium without reference to atomic hypotheses. But, in the present state of knowledge, such a doctrine seems limited in its scope, and cases in which it ceases to be sufficient will constantly recur in this volume. For instance, the phenomena of highly rarified gases have only been interpreted successfully by the aid of strictly molecular conceptions. The passage of electricity through gases, which will be considered in a future chapter, leads directly to molecular hypotheses, and, in conjunction with the phenomena of radio-activity, gives an extended insight into the intimate structure of atoms and molecules. In such matters we are driven back to molecular theory, which offers an alternative method of correlating other phenomena also, equally definite, if in some ways more speculative.

Thermodynamic theory, as well as practical experiment, thus indicates that the osmotic pressure of a solution depends only on the number of dissolved particles, and not on their nature or on the nature of the solvent. The phenomena of gases show that the number of molecules in two

systems may be compared by a knowledge of the total masses and of the chemical molecular weights. Thus, two solutions, one of sugar, let us suppose, and one of alcohol, which are prepared so as to contain the same number of molecules in the same volume, both in theory and practice, possess equal osmotic pressures. But, if equimolecular solutions of sugar and salt be examined, the osmotic pressure of the salt is found to be greater, and, if the solutions be dilute, nearly twice as great as that of the sugar. These abnormally great osmotic pressures were discovered at an early date in the history of the subject; and further investigation showed that, at all events when the solvent was water, they occurred in the cases of those solutions which were conductors of electricity.

When Van't Hoff formulated the physical theory of the osmotic pressure, he treated these abnormal values as exceptions to the usual law. It was reserved for the physicists Arrhenius of Stockholm and Planck of Berlin to point out that the extension of Van't Hoff's principles to these cases required the assumption of the dissociation of the molecules of salt in order that the total number of particles in solution should still be the number indicated by the observed phenomena. According to this hypothesis, in a dilute solution of common salt, the solute does not exist as molecules of

sodium chloride, but as the dissociated parts, sodium and chlorine, which, since the solution conducts a current of electricity, must be associated with electric charges. Each salt molecule thus gives two pressure-producing particles in solution, and the double value of the osmotic pressure is explained. In stronger solutions this dissociation is not complete, and the osmotic pressure is less than twice the normal value; but no exact correlation of pressure and dissociation can be made, for the thermodynamic theory as formulated above is only valid for very dilute solutions.

Like the thermodynamic theory of osmotic pressure generally, this extension of it does not involve any particular view as to the cause of the pressure or the nature of solution. The dissociation hypothesis is concerned simply with the difference between solutions of electrolytes and non-electrolytes, and leaves entirely open the more fundamental question, whether solution is essentially chemical or physical in its nature.

The dissociation theory of aqueous solutions of electrolytes, originally indicated by osmotic phenomena, is supported perhaps even more clearly and strongly, by the study of the electrical properties. During the years 1830 to 1840,

Faraday made a series of experiments on the passage of electricity through liquids, in this way laying the foundations of our quantitative knowledge of that subject. He showed that the transfer of a given quantity of electricity was always accompanied by the liberation of a definite quantity of one of the constituents of the solution, a quantity proportional to the total electric transfer, and to the chemical equivalent weight of the substance liberated. The quantity of electricity which passed, then, depended on the number of chemical equivalents of substance liberated and not on their nature. These results led to a definite view as to the nature of the process of electrolysis. We must regard the passage of an electric current through a solution as due to the carriage by moving parts of the salt of opposite electric charges in opposite directions through the liquid. Under the influence of applied electric forces, these carriers drift through the solution, and finally give up their charges to the electrodes, as the terminals by which the current enters and leaves the solution are called. With common salt, for example, a stream of positively electrified sodium drifts with the electric current, while negatively electrified chlorine passes in the opposite direction. The moving parts of the salt, with their accompanying electric charges,

were named ions by Faraday; the positive ion which moves down the electric current, is termed the cation, and the negative ion which travels up the electric stream is called the anion. The electrodes to which they travel are known as the cathode and anode respectively. The electric charge on a single ion of a substance like sodium or chlorine constitutes a true natural unit of electricity. No smaller quantity seems capable of existing. As Helmholtz has insisted, electricity, like matter, is not infinitely divisible; it possesses an atomic structure.

In the year 1855 Hittorf examined the changes in the concentration of a solution which occur on the passage of an electric current, and explained them by supposing that the two ions moved at unequal rates. It is evident that more salt will be taken from that end of the solution from which comes the more mobile ion, and, on the assumption that this is the only cause at work, Hittorf calculated the ratio between the velocities of the two ions in many cases.

The next great step was made by Kohlrausch, in 1873. The conductivity of a solution is measured by the total quantity of electricity which passes through the solution per second under the action of a given electric force; and, since the current is carried by the motion of

charged ions, the conductivity must depend on the number of the ions, that is, on the concentration of the solution, and on the velocity with which the opposite ions move through the liquid. Thus, by measuring the conductivity, the velocities of the ions under a given electric force can be calculated.

So far the movement of the ions was visible to the mind's eye only. Their passage through a solution seemed necessary to explain the facts, and, in an indirect way, their velocities could be calculated, but no direct evidence of the reality of these hypothetical phenomena was forthcoming. However, in the year 1886 Sir Oliver Lodge, and shortly afterwards by a somewhat different method the present writer, showed how to render these molecular processes visible, and how to watch the motion of the ions as they drift through the solution under the action of the electric forces.

One apparatus which may be used for this purpose is represented in Fig. 26. Let us suppose that a solution of some coloured salt is placed in contact with the solution of some colourless one, so that a fairly sharp line of demarcation is produced between them. The solutions should be of the same molecular concentration, the same conductivity, and the denser solution

must, of course, be placed below the lighter. Let us take, as an example, the case of solutions of potassium bichromate and potassium carbonate, which fulfil the necessary conditions. The colour is here due to the acid part of the salt, the bichromate ion, which has the chemical composition represented by $Cr_2O_7$; the potassium ion is colourless. When a current of electricity is passed across the junction between the liquids, the colour boundary is seen to move, and, from the rate at which it creeps along the tube, the velocity of the bichromate ion under a given electric force can be determined.

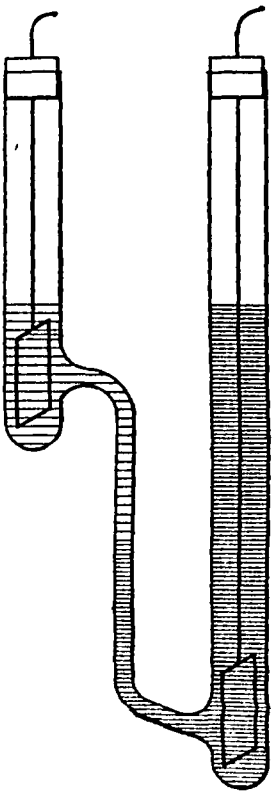


FIG. 26.

The conductivity of a salt solution, made solid by the addition of gelatine or some similar substance, is nearly the same as that of the liquid solution without the jelly, and this fact justifies the use of such solid solutions in experiments on the migration of ions. Lodge determined the

velocity of the hydrogen ion by watching the rate at which, passing along a glass tube, it changed the colour of an indicator, while the present writer has measured the velocity of many other ions by tracing the formation of opaque precipitates, formed in minute quantity by the ions in their path.

Of late years these methods have been improved and extended by Orme-Masson and B. D. Steele. The general result of the experiments is to confirm the values for the ionic velocities calculated from the theories of Kohlrausch and Hittorf.

The velocities with which the ions travel, even when driven forward by intense electric forces, are very small. Hydrogen, the most mobile ion known, moves over a distance of ten centimetres, or four inches, in one hour, when the applied electromotive force is one volt per centimetre. Most other ions travel at about one-tenth this rate.

These comparatively small velocities must not be confounded with an entirely different thing: the velocity with which an electric impulse, started at one end of a tube filled with an electrolyte, reaches the other end. This velocity is very great, closely approaching the rate at which an electro-magnetic wave travels through free space, that is, the velocity of light, about one hundred and eighty thousand miles a second.

If we accept for the moment the common conception of an electric current as analogous to the flow of a liquid through a conducting pipe, the connection between the two modes of motion may be illustrated by a familiar example. Suppose that a long wooden rod is lying on the surface of the ground, and that a push is given to one end of it. The motion of the rod may be quite slow, an inch an hour if we like. But, after moving one end, the other end begins to move an extremely minute fraction of a second after the starting of the impulse. Perhaps it never has occurred to us that any appreciable time elapses between the starting of the two ends. Yet, if we think for a moment, it is clear that the initial push must travel as a wave of compression along the rod, and that the far end can only begin to move when the wave front reaches it. The bearing of the analogy is now obvious. The slow movement of the rod as a whole when once started corresponds with the slow drift of the ions; the almost instantaneous passage of the wave of compression along the rod corresponds with the velocity of electricity in the electrolytic solution.

A picture of the phenomena, more nearly corresponding with the facts, is obtained by considering that the rapid electric impulse travels as an electric wave through the surrounding luminiferous æther.

On this view, due to Faraday and Maxwell, and now universally accepted, the electric forces always travel through the æther. When they act on charged matter free to move, as in metallic conductors or electrolytic solutions, they produce a drift of that matter—a drift which constitutes a current. Along the line of the drift, that is, along a conductor, energy is lost, and thus along that line, and there alone, energy is constantly flowing, being carried forward by the æther to supply the place of the energy dissipated by the current.

The mobility of any one ion is, in dilute solutions, independent of the nature of the other ion present, at all events in simple salts, such as the chlorides of sodium, potassium, and lithium. This independence itself indicates that the ions are independent of each other, and again suggests some form of dissociation.

The phenomena of conductivity also point to the same idea. To set free an ion or its products at the electrodes requires the expenditure of a certain amount of electric work, and at the electrodes an equivalent reverse electro-motive force exists. When, however, this reverse force is overcome, the passage of the current through the solution is opposed by no other reversible forces, and it is found that the work expended is that

required to force the current against the resistance of the electrolyte alone. The current is proportional to the excess of the electric force applied beyond what is needed to overcome the effect at the electrodes; this part of the conduction conforms with Ohm's law, which describes the process in metallic conductors. In the body of the solution, then, as distinct from the transition layer in contact with the electrodes, the electric forces do no reversible work, such as would be needed to separate the ions from each other. Whatever freedom is requisite between the ions for the purpose of conduction, must necessarily exist whether the electric forces act or not; the function of the electric forces when applied is simply to force the ions, already separated from each other, against the frictional resistance of the liquid medium. A certain freedom of interchange, at all events, is thus indicated between the ions, and the freedom of interchange exists whether the current passes or not. Such freedom, indeed, had long ago been inferred from the phenomena of double decomposition observed in the chemical reactions between solutions of different salts.

So far the conductivity relations indicate the possibility of ionic interchange between the parts of the dissolved molecules, though the conformity of

solutions with Ohm's law does not, of itself, necessitate the idea of permanent ionic freedom. But on any other view the possibility of interchange must be secured by collisions between the dissolved molecules, and consequent interchanges between their ions, which would thus work their way through the solution by a series of such collisions. The velocity with which this process was effected must then depend on the frequency of collision, which would be proportional to the square of the concentration. The ionic velocities, then, on this supposition, would increase in proportion to the square of the concentration of the solution, and the conductivity, which depends on the product of the ionic velocities and the concentration, would vary as the cube or third power of the concentration.

But the facts are quite inconsistent with this hypothesis. The conductivity is proportional at the most to the first power of the concentration; and the ionic velocities, instead of increasing as the square, are, in dilute solution, independent of the concentration, and in more concentrated solutions decrease with increasing concentration. We are thus again driven to the belief that the ions are free from each other, and move independently of each other through the liquid under an electric force: free from union with each other, let us

observe, not necessarily free from combination, chemical or other, with the solvent. As already indicated, the dissociation theory does not depend on any particular view as to the nature of solution in general.

For aqueous solutions, then, the evidence in favour of the dissociation hypothesis is very strong, and it can safely be used as a working hypothesis to co-ordinate the known phenomena, and to guide future research. For solutions in other solvents, less evidence is yet available; though for solutions of certain salts in alcohol, the laws of the electrolysis seem to be similar to those of aqueous solutions and to indicate a similar theory. In fused salts, and solid electrolytes like the filaments of Nernst lamps, which also conduct currents of electricity, the conditions are different, and we must wait for further light before we can profitably examine the nature of the conduction process.

Besides explaining the electrical and osmotic properties of solutions, the dissociation theory has proved one of the most fruitful generalisations in the domain of chemistry that have ever been formulated. Solutions of salts and acids, electrolytes in fact, are the solutions which exhibit chemical activity in the highest degree. In them, the ions alone are concerned in chemical

action, and so clearly is this the case, that, as soon as the subject is examined, the ordinary chemical tests for the presence of salts are seen at once to be, in reality, tests for the individual ions of those salts. At one time it seemed likely that all cases of rapid chemical action might be reduced to reactions between electrolytic ions, but recent work by Kahlenberg and others seems to show that in non-aqueous solvents rapid reactions may occur not in any way correlated with electrolytic conductivity. However this may be, in water many chemical actions are certainly connected in a very intimate way with the electrical properties, and the dissociation theory gives a satisfactory method of co-ordinating the two sets of properties. In some reactions the actual electric charges on the ions seem to be the determining factors of the whole process.

There is a marked difference in chemical and physical properties between bodies of definite crystalline form, such as most inorganic salts, and soft or amorphous substances, such as albumen and the various kinds of jelly. Long ago Graham distinguished the two groups as crystalloids and colloids respectively, and particularly examined them with regard to their

relative powers of diffusion through water. He found that, while crystalloids diffuse comparatively rapidly, the motion of colloids is so slow that it is often almost inappreciable.

Many different kinds of chemical compounds show colloidal properties. Besides a vast number of animal and vegetable substances, some of which seem to play a great part in the phenomena distinctive of living matter, many of the precipitates which are formed in the course of inorganic chemical reactions appear in an amorphous or colloidal state. The sulphides of such metals as antimony and arsenic are good examples. If a solution of arsenious acid is allowed to flow into water kept saturated with sulphuretted hydrogen by means of a current of that gas, a colloidal hydrosulphide is formed. Many hydrates, too, are colloids, ferric hydrate, for instance, which can readily be prepared from the corresponding salts of iron. By treating dilute solutions of gold chloride with reducing agents, such as a few drops of a solution of phosphorus in ether, the gold is set free in the colloidal condition, forming a ruby-coloured solution. Silver, bismuth, and mercury can also be obtained in colloidal solution.

Crystalloids diffuse much more rapidly through water and other solvents than do colloids. If

a mixture of crystalloids and colloids be placed in a drum covered with a colloidal membrane, such as bladder or parchment, complete separation can be effected, for the dissolved colloids seem quite incapable of passing through such membranes. This process probably plays a great part in animal and vegetable physiology.

Solutions of colloids in crystalloid solvents, such as water or alcohol, seem to be divisible into two classes. Both classes appear to mix with warm water in all proportions, and the mass will solidify under certain conditions to form a solid which may be called a gel. One class, represented by gelatine and agar jelly, will, when solidified, redissolve on warming or dilution, while the other class, containing such substances as hydrated silica, albumen, aud metallic hydro-sulphides, will, under the influence of heat or on the addition of electrolytes, form gels which cannot be redissolved. The solidification of members of the first class into redissolvable substances is termed setting, that of substances in the second class, which form insoluble precipitates, is termed coagulation.

The mechanism of gelation in the first, or reversible class of colloidal systems, has been studied experimentally by Van Bemmelen and by W. B. Hardy. The process of solidification

seems to consist in the growth of a solid framework containing more liquid portions. The temperature at which this separation into two phases occurs depends on the amount of water present.

The coagulation of irreversible colloidal solutions, as already stated, can be effected by the addition of small quantities of the solution of an electrolyte, such as an ordinary salt or acid. Graham, who originally investigated the subject, found that a minute trace of salt was often sufficient. Thus, hydrated alumina, prepared from a solution of the chloride, was so unstable that a few drops of well-water at once produced coagulation, and the same change was brought about by pouring the colloidal solution into a new glass vessel, unless the vessel had previously been washed repeatedly with distilled water.

Several experimenters, including Schulze, Linder and Picton, and Hardy, have recently worked at this coagulative power of electrolytes, with very curious and interesting results. The coagulative power of a salt is found to vary in a remarkable manner with the chemical valency of one of its ions.[1] The average of the coagu-

[1] The valency of a chemical atom may be defined as the number of hydrogen atoms it will combine with or replace. Thus the normal valency of oxygen is two, since two hydrogen atoms unite with one oxygen atom to form water. Faraday's work showed that the electric charge carried by an ion is proportional to its valency.

lative powers of salts of univalent, divalent, and trivalent metals are found to be proportional to the numbers 1 : 35 : 1023 respectively. Most properties which depend on the valency vary in the ratios 1 : 2 : 3, and the great difference in the numbers now under consideration is very striking. An explanation of these unusual relations has been given by the present writer.

Let us now frame a mental picture of a solution as it is represented by the dissociation theory. A certain number of the dissolved molecules are regarded as dissociated into charged ions, which wander, free from each other, through the liquid, perhaps by successive combinations with solvent molecules in their path. When an electric force is applied, though still moving sometimes in one direction and sometimes in another, the ions, on the whole, drift in the direction indicated by the force, and we may therefore imagine that two processions of oppositely charged ions pass each other, drifting in opposite directions through the solution.

When there is no electric force, the ions are subject to no steady drift, and must move sometimes in one direction, sometimes in another, as the chances of their life direct. Any one ion will sometimes be passing from one solvent molecule to another carrying its electric charge with it;

sometimes it will come across an ion of the opposite kind in such a way that combination occurs, and, for a time, an electrically neutral molecule is formed. By collisions of unusual violence, or by other means, this moleculé will soon be dissociated, and its ions again set free from each other, to be handed backwards and forwards by the solvent molecules as already described.

Let us suppose that, in order to produce the aggregation of colloidal particles which constitute coagulation, a certain minimum electric charge has to be brought within reach of a colloidal group, and that such conjunctions must occur with a certain minimum frequency throughout the solution. Since the electric charge on an ion is proportional to its valency, we shall get equal charges by the conjunction of $2n$ triads, $3n$ diads, or $6n$ monads, where $n$ is any whole number.

The chance conjunctions of a large number of particles moving like the ions of an electrolytic solution can be investigated by the principles of the kinetic theory of gases. If $1/x$ denote the chance of one ion colliding with a colloidal particle, the chance that two ions should collide with it is the product of their separate chances, or $1/x^2$, and so on. When applied to the case in hand, these principles lead to the

conclusion that the relative coagulative powers of univalent, divalent, and trivalent ions will be proportional to the ratios $1 : n : n^2$. The value of $n$, which depends on a number of unknown factors, remains arbitrary. If we assume that $n$ is 32, $n^2$ is 1024, and we get the numbers 1 : 32 : 1024 to compare with the experimental values of the relative coagulative powers 1 : 35 : 1023.

When we consider the difficulty of the experiments, and remember that the coagulative powers of different solutions containing ions of equal valency are not exactly equal, but vary as the equivalent conductivities of the solutions, we see that these results show a remarkable agreement with the calculated numbers, and give strong evidence in favour of the hypothesis that coagulation depends on the presence of a minimum electric charge, which is brought into action by the chance conjunction of the ions of an electrolyte.

The particles in solutions of colloids in water generally move slowly when acted on by electric forces, the direction of motion depending on the nature of the colloid and on that of the solvent. Hardy found that the direction of movement of certain proteids could be changed by changing the solvent from a very dilute acid to a very dilute alkali. This reversal implied a change in the sign of

the charges on the colloid particles ; and, if the solvent was very carefully neutralised, an iso-electric point was reached at which the solution became very unstable, and coagulation seemed to occur spontaneously. The same observer also found that, in the case of colloids travelling with the current, it is the acid ion which is active in causing coagulation, and not the metallic ion as in the experiments of the older experimenters, who all used colloids which travel against the electric current. Thus it is always the ion possessing a charge of opposite kind to that on the colloid particle which is effective in producing coagulation.

These results are of great importance, not only from the point of view of physiology, from which they were undertaken, but also as throwing light on the nature of colloid solution, perhaps, indeed, of solution in general. It looks as though colloid particles, at any rate, could exist in solution only when charged electrically. If, by the conjunction of more mobile ions, their charge is neutralised and the iso-electric point reached, coagulation must immediately follow.

It is probable that these effects depend on changes in the surface of separation between the colloidal particles and the more liquid phase which surrounds them. Such a surface of separation must exhibit the well-known

phenomena of surface-tension, and will possess an amount of available energy proportional to its area, which therefore tends to become as small as possible. A number of separate particles would, in these conditions, tend to coagulate into larger ones, just as small raindrops tend to coalesce into larger ones. If the colloidal particles are electrified, the electric energy is greater when the charge is concentrated on a small area, and, on this account, the area will tend to increase. The effect of the electric charge is thus opposite to that of the natural surface-tension, and diminishes the tendency to coagulate. Thus an electric charge may enable the colloid to dissolve, while neutralisation of the charge may result in coagulation.

Modern physiology finds some reason for believing that a wave of this electrolytic coagulation is the physical accompaniment of a nerve impulse, while permanent and irreversible coagulation results from the action of certain poisons. This, however, is not the place to follow in detail such an interesting inquiry, which deals with matters outside the present scope of physical science.

Much discussion has taken place about the nature of liquid colloidal solutions, and their relations with ordinary solutions of mineral salts

and other crystalloids. They may either be regarded as ordinary solutions, in which the dissolved particles are similar in kind to those of crystalloid solutions, though of much higher molecular weight, or they may be considered to be systems of two phases, composed of suspensions of particles in the liquid, different from it, and of much greater than molecular dimensions.

In some colloid solutions the presence of suspended particles can readily be detected by ordinary means. Sometimes they may be visible under a good microscope; in other cases, while too small to be directly visible, they are large enough to scatter and polarise a beam of light. This means that their size must be comparable with the wave-length of light, about $5 \times 10^{-5}$ C. Such particles would be too few in number to exert a measurable osmotic pressure, and the absence of such pressure does not necessarily mean that solutions of colloids are different in kind from solutions of crystalloids.

It is worthy of note that turbid suspensions of clay, kaoline, &c., in water are rapidly cleared by the addition of small quantities of metallic salts. This action, which is almost certainly of the same nature as the coagulation described above, probably helps in the formation of sand-banks at the mouths of rivers; the salts of the sea-water clear

the suspensions of clay brought down with the fresh water, and precipitation is then aided by the diminished velocity.

The conditions which determine the colloid or crystalloid nature of a substance are still not fully understood. The persistence of colloid properties, when a substance passes from the dissolved to the non-dissolved state, shows that the determining conditions must be of fundamental importance. The molecular forces seem to be much less active in colloids, but the freedom with which some of them disintegrate and dissolve in presence of water and other liquids indicates that some interaction between them and their solvent must occur. It seems likely that the forces which are involved in crystalloid solution are of the nature of those classed as chemical or molecular, while, when colloids dissolve, the actions between solvent and solute are conditioned also by the phenomena studied under the names of capillarity and surface tension. It is not likely that any sharp line of demarcation can be drawn; though, as the size of the dissolved particles increases, the importance of the chemical forces probably diminishes, and that of the capillary forces grows.

If colloid and crystalloid solution are but the extreme limits of a continuous series of phenomena, the study of dissolved colloids of varying degrees

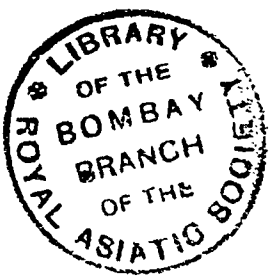
of aggregation should throw much light on the general problem of the fundamental nature of solution.

The explanation of the coagulation of colloidal solutions as an effect on the surface conditions at the junction between colloid and solvent, brought about by the chance conjunctions of dissociated electric ions, is an illustration of a course of history which indeed constantly repeats itself in scientific inquiry. An observation is made, perhaps long series of experiments are carried out, before the general state of knowledge enables a satisfactory explanation of the phenomena to be formed, or a theoretical co-ordination of them with other phenomena to be traced. Even Graham's acute and powerful mind, in the absence of the dissociation theory of electrolytes, and of the knowledge of the surface relations of two phases which we now possess, could frame no complete theory of the coagulation effects which he examined with such skill. By experiments on coagulation alone it is probable than an explanation could never have been reached. But by the advance of other observers, led by Gibbs on one far-off flank, and by Van't Hoff and Arrhenius on the other, almost out of touch with the original attack, the position of the adversary

—ignorance—was turned; and when, at a later time, a new frontal assault was made, the way proved easy and obvious.

"For, while the tired waves, vainly breaking,
Seem here no painful inch to gain,
Far back, through creeks and inlets making,
Comes, silent, flooding in, the main.

And not by eastern windows only,
When daylight comes, comes in the light;
In front the Sun climbs slow, how slowly!
But westward, look! the land is bright."


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# CHAPTER V

## THE CONDUCTION OF ELECTRICITY THROUGH GASES

"It is difficult to think of a single branch of the physical sciences in which these advances are not of fundamental importance. . . . The physicist sees the relations between electricity and matter laid bare in a manner hardly hoped for hitherto. . . . But it is the philosopher that these researches will affect most profoundly. As much by the aid of a perfect mastery over the properties of materials as by the sheer intellectual power of abstract reasoning, some of the fundamental problems of the constitution of matter are here presented as on the verge of solution."—*Times*, January 22, 1904.

UNLIKE the liquid solutions and other electrolytes studied in the last chapter, gases, in normal conditions, are almost perfect insulators of electricity. Telegraph wires are insulated by the air which surrounds them, and, if leakage occurs to any measurable extent, it can always be traced to the solid supports to which the wires are attached. Nevertheless, by delicate instruments, a slight leakage of electricity through air can be detected. This air leakage is usually extremely small, but it can be increased greatly in many ways. The passage of Röntgen rays, the incidence of ultra-violet light on a metal plate, the neighbourhood



J. J. Thomson

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of flames, incandescent metals, or of radio-active bodies such as radium, are among the ionizing agencies whereby the condition of the surrounding air is modified so that it can rapidly conduct away the electric charge.

In general, the currents through gases are too small to be investigated by means of a galvanometer. By the aid of an electrometer, however, or by the use of some form of gold leaf electroscope, the passage of electricity may be detected, and the amount of the current determined.

The quadrant electrometer consists of a light needle of aluminium or silvered paper, suspended by a fine quartz fibre. The needle is kept charged with electricity, and is therefore deflected when other charges are given to brass quadrants which surround it. By the rate at which the deflection of the needle diminishes, it is possible to estimate the rate at which the charge on the quadrants, and on any conductor connected with them, disappears or increases.

Still simpler and yet more sensitive is the gold leaf electroscope, in which a thin strip of gold leaf is attached to a brass plate, and charged with electricity. Owing to the repulsive forces between portions of the same charge, the gold leaf is repelled from the plate and stands out at an angle. By observing through a microscope the

rate at which the leaf falls, we can determine the rate at which its charge leaks away.

Whichever apparatus is adopted, the natural leak, due to the apparatus itself and the air surrounding it, must first be determined, and subtracted from the leakage afterwards found under the influence of an ionizing agency.

In the last chapter we have seen that the properties of conducting solutions have been successfully co-ordinated and explained on the hypothesis that the passage of a current is effected by the motion of charged particles called ions. A similar supposition has been adopted to explain the conductivity of gases, although it will be clear that, in many respects, the ions in the case of electric discharge through gases must be endowed with properties different from those which pertain to the ions of liquid solutions.

After a period of activity on the part of some ionizing agency, such as Röntgen rays, the resultant conductivity does not cease simultaneously with the action of the rays. It persists for some little time; it can be blown about with currents of air; and in all respects acts as though it were due to the presence of material particles, formed somehow in the gas through which the rays had passed. The conductivity is destroyed if the gas be passed through a plug of glass wool or bubbled through

water; it is also removed if the gas be subjected to the action of an electric field. Such experiments, and many others of somewhat similar nature, are readily explained by the conception of charged particles, which, produced in some way by the action of the ionizing agency on the molecules of the gas, are afterwards driven through the gas by an electric force, just as the ions of a salt solution are driven through the liquid. Unlike the ions of liquids, however, those of gases do not long persist after the cessation of the outside ionizing agency. Left to themselves, the ions gradually disappear. Such a disappearance might be anticipated on the view that the opposite ions re-combine and neutralize each other, and also on the assumption that they give up their charges to the solid objects with which they come in contact as they move about under their own motions of diffusion, and that they are driven towards an electrode by the action of an electric force.

The non-persistence of gaseous ions and the consequent need of their perpetual renewal explains the relation between current and electro-motive force — a relation different from that observed in liquid solutions. In solutions, as we saw, the conduction conforms with Ohm's law—the current is proportional to the electro-motive force.

In gases this is not the case. For an ionizing agency of constant intensity, such as a layer of oxide of uranium, the current at first rises with the applied electro-motive force, but it soon tends towards a limit, and finally reaches a maximum, when, till we approach the sparking point, no further increase of electro-motive force will

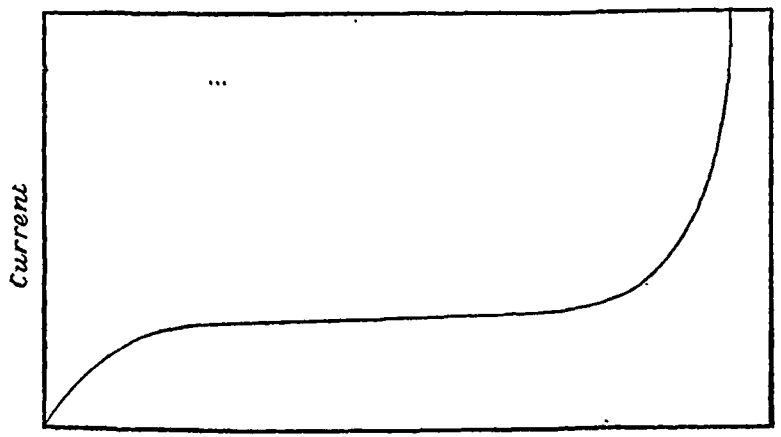



FIG. 27.

produce any appreciable increase of current. This saturation current, as it is called, is represented by the horizontal part of the curve in Fig. 27. Obviously it corresponds to a state in which all the ions are removed to the electrodes as fast as they are produced by the ionizing agency.

As the sparking point is approached, the curve shows that the current again rises rapidly ; the applied electric force being strong enough to produce ions in the gas by its own action. Townsend has shown that this process is effected by the collision with the gas molecules of ions already present, which are driven forward by the electric force with high velocity. In this way are formed most of the ions which carry the current in an electric spark, or in the arc discharge.

We have already described the methods of calculating the velocities with which the ions of liquids move under known electric forces, and of determining those velocities by direct experiment. For gaseous ions, the corresponding velocities are much higher. They have been determined in several indirect ways, with concordant results. For instance, Zeleny measured the electric force required to push an ion against a stream of gas, moving with a known and uniform velocity in the opposite direction to the natural motion of the ion. Langevin, in 1902, attacked the problem in another way. The gas between two parallel electrodes was exposed momentarily to the action of Röntgen rays. The ions thus produced may disappear in two ways. Opposite ions may re-combine with each other, or they may pass to the electrodes under the influence of an electric force. If the

force be great, the latter method alone is operative, the number of ions re-combining before reaching the electrodes being very small. If, then, the electric field be kept acting in one direction, all the positive ions produced by the Röntgen rays will go to one electrode, and all the negative ions to the other. But if the electric force be reversed before all the ions get across, the charge received by an electrode would be less than before. Thus, measurement of the charges received by the electrodes with different speeds of reversal will give a means of calculating the velocities of the ions. At atmospheric pressure, under a potential gradient of one volt per centimetre, the velocities of different ions vary from about three-quarters of a centimetre per second in the case of carbon dioxide, to about seven centimetres per second in the case of hydrogen. The velocity of the negative ion is, in general, appreciably greater than that of the positive ion, the ratio, unity for carbon dioxide, rising to 1.24 for air and oxygen.

We should expect the velocity of an ion to be inversely proportional to the pressure of the gas, and this has been found to be the case with the positive ions. The mobility of the negative ions, on the other hand, increases with decreasing pressure much faster than this expectation justifies, and at low pressures, 100 millimetres of mercury

and less, the change is very marked. This result indicates an alteration in the nature of the ions themselves, and justifies the belief that they must possess more complex structures at high than at low pressures.

We shall see later that, at the very low pressures which exist in good vacuum tubes, it is possible to estimate the absolute mass of the ions, with the remarkable result that, whereas the mass of the positive ion appears to be much the same as the mass of an atom, the mass of the negative ion comes out about the thousandth part of the mass of the lightest atom known to chemistry, that of hydrogen. The decrease of the ionic velocity at low pressures probably indicates an approach to this state of low ionic mass.

A similar decrease in the size of the negative ion, compared with that of the positive, is produced by raising the temperature. H. A. Wilson found that, at 2000° C., the velocity of the negative ions, produced by salts volatilised in flames, was seventeen times greater than the velocity of the positive ions.

The problem of determining the dimensions of the ions at atmospheric pressure has been attacked by measuring their rates of diffusion into non-ionized gases. The rate of diffusion of a gas depends on the mass of its molecule, and experi-

ments show that the mass of an ion at atmospheric pressure is considerably greater than that of the molecule of an ordinary gas.

All these results may be explained by the theory that the normal process of gaseous ionization consists in the detachment from an atom of the gas of a minute particle, called by Professor J. J. Thomson a corpuscle. At extremely low pressures the corpuscle constitutes the negative ion, and the atom or molecule from which it has been separated forms the positive ion. As the pressure rises, neutral molecules become attached to the ions, probably by virtue of the electric forces, and collect round the original ion, which constitutes the nucleus. These complex systems form the ions of gases at atmospheric pressures.

The presence of gaseous ions may be inferred from the phenomena of current conduction through the gases, but the existence of charged particles of greater than molecular dimensions has been demonstrated by Mr. C. T. R. Wilson in a very direct and striking manner. Long ago Aitken showed that the condensation of drops of water from air saturated with aqueous vapour was much helped by the presence of particles of dust; in the absence of dust, considerable supersaturation could be attained before condensation set in.

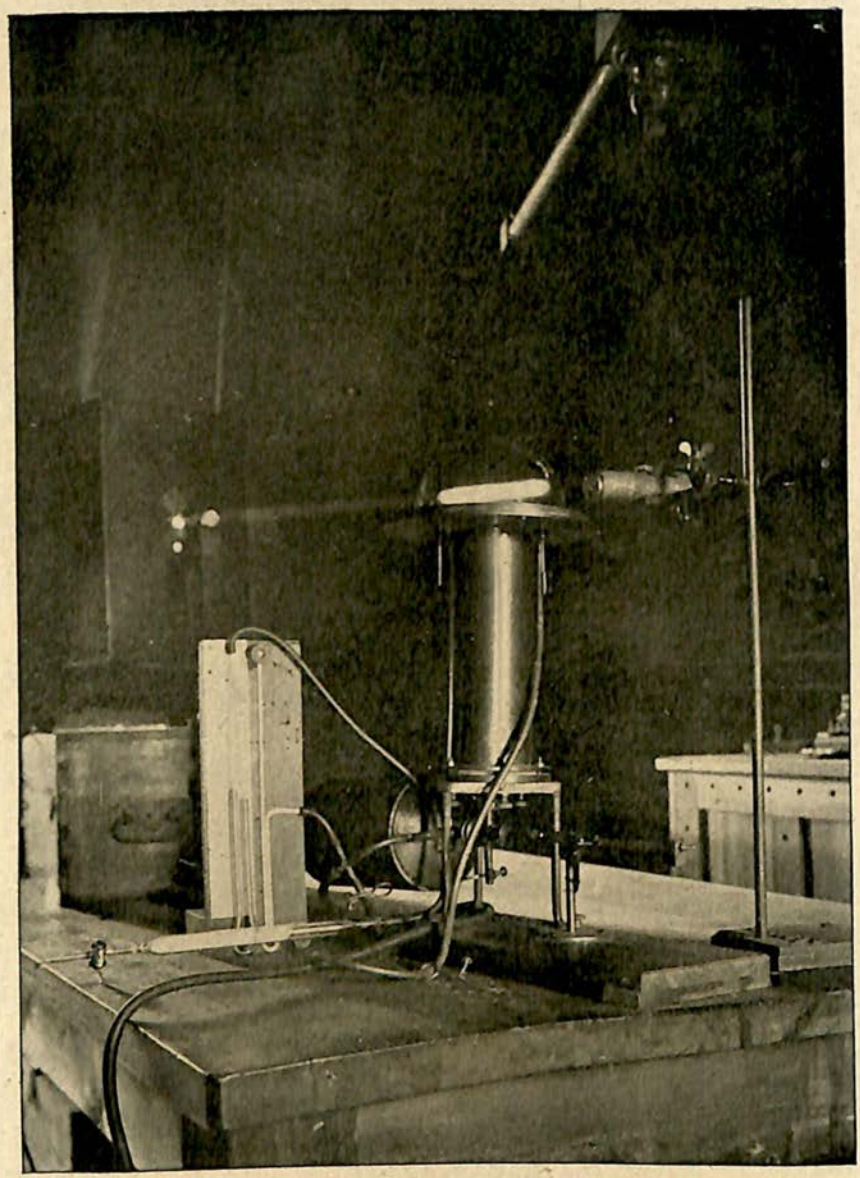


FIG. 28.—CONDENSATION OF CLOUD ON GASEOUS IONS
(*Mr. C. T. R. Wilson*)

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Each particle of dust forms a nucleus, round which collect molecules of water; and, when the drops have grown to a sufficient size, they fall, carrying down the dust particle also. In this way finally the air is freed from the presence of dust, and to this action, on a large scale, we must attribute partially the clearness of the atmosphere after a downfall of rain.

Wilson devised an apparatus whereby air could be subjected to a sudden expansion. By this means it was cooled; and, if previously saturated with water vapour, any desired degree of supersaturation could be obtained by adjusting the amount of expansion. By repeated expansions, the dust particles were removed, and any further expansions then produced only a few drops of water. If, however, when the air had thus been depleted of possible nuclei, Röntgen rays or other ionizing agency were allowed to act on the gas, instead of these few drops, a dense cloud was once more obtained by the same expansion. This cloud was not formed if the ions were removed previously by an electric field, or by some other means.

Fig. 28 is a photograph of one of Mr. Wilson's clouds, illuminated by a beam of light from an electric lantern. The nuclei in this case were the ions produced by a piece of radium contained in the tube seen to the right of the glass cloud-

chamber. The cloud has settled down to the lower part of the hemispherical chamber, and its sharply-defined upper surface is clearly visible. The expansion is effected by the movement of a piston within the vertical brass cylinder, the lower part of which is put suddenly into communication with the exhausted vessel seen lying on the table.

In 1893, Professor Thomson had shown that, in causing condensation, negative electrification was more effective than positive, and Wilson, in 1899, further examined this point. He found that, while negative ions produced condensation of a cloud when the volume of the gas was increased in the ratio of 1 : 1.28, positive ions did not cause an equal effect till the expansion reached 1.31. It is possible that this difference may have an important meteorological significance. If, as there is reason to suppose, the atmosphere sometimes contains a considerable number of gaseous ions, an expansion or fall of temperature would result in the formation of drops of water round the negative ions sooner than round the positive ions. The negative ions thus would be removed first, and the air would be left with an excess of positive electrification. It is not unlikely that the origin of the commonly observed potential of the atmosphere, positive relatively to that of the earth,

is, partially at any rate, to be found in this selective withdrawal of the negative ions.

If the ionization be not too intense, it is possible to remove completely the ions from air by means of a single expansion. Each ion will then be the nucleus of a water-drop ; and, since the amount of water left in the air must be just that required for the equilibrium of saturation, the quantity of water removed by the falling cloud can be calculated. This amount of water is constant for a given expansion, and the number of ions present must therefore be the factor which determines the size of the drops. Minute drops, the constituent parts of the artificial cloud or fog under consideration, fall very slowly, and Sir George Stokes has shown how their size may be calculated from the rate of their fall. The cloud settles down at a steady, well-marked pace, which can readily be observed by watching the upper surface as seen in Fig. 28. This measurement gives the average size of each drop ; and, since the total mass of all the drops can be calculated from the expansion, the total number of drops, and therefore of ions, can be deduced approximately.

J. J. Thomson has used this method to determine the electric charge on a gaseous ion. The current through the gas is given by the product of the number of ions, the charge carried by each, and

the velocity with which they move. The velocity, as we have said, can be determined for a known electro-motive force ; and, by measuring the resultant current with an electrometer, and finding the number of ions by Wilson's method, the ionic charge was estimated. Within the limits of experimental error it was found to be the same as the charge on an ion in liquid electrolysis, and to have the value $3.4 \times 10^{-10}$ electro-static units. The importance of this result will appear later.

We must now consider another series of experiments in which these particles, called variously ions, corpuscles, and ultra-atomic bodies, have been detected. The investigations were originally planned and carried out to determine other points of interest, and only comparatively recently have they been used to elucidate the present subject matter.

An electric machine capable of yielding sparks was invented many years ago during the eighteenth century ; and the question soon arose whether such sparks were of the same nature as the lightning flash—whether the roll of the thunder was but the reiterated crackle of the stupendous electric machine of the atmosphere working amid the convolutions of the clouds. The question was answered by Franklin, who floated a kite in the

air, and, when the string was made a conductor by a shower of rain, was able to draw the confirming sparks from its lower end.

A very great electric force is required to maintain a visible discharge through a few centimetres of air at the atmospheric pressure, and the initial force needed to start the process is still larger. It was soon found, however, that a reduction of pressure facilitated the passage of the spark, and that it was much easier to send the discharge through a vessel from which the air had been partially exhausted by means of an air-pump. To illustrate this, platinum wires, to act as electrodes, are sealed into little glass tubes containing air at low pressure. For many years these vacuum tubes, as they are called, were the electrical playthings of the laboratory and popular lecture-room. Recent discoveries have raised them from the position of scientific toys to the rank of pieces of apparatus whereby have been made some of the greatest discoveries in physical knowledge that the present generation has seen.

Through such a tube, in which the pressure of the air is only a small part of an atmosphere, a discharge may readily be passed by the aid of a voltaic battery and an induction coil, or by the use of an influence electric machine. As in liquid conductors, the electrode by which the current

enters is called the anode, and that by which it leaves, the cathode. Starting from the cathode, we first see a bright glow covering its surface, then a dark space, succeeded by a second dark space, beyond which is a luminous column reaching to the anode. Within certain limits of pressure and strength of current, this positive column, as it has been called, shows fluctuating striations. If the length of the tube be increased, it is this positive column alone which increases with it; the two dark spaces, and the negative glow, vary very little with the length of the tube.

The effect of very high vacua on the electric discharge was first systematically investigated by Sir William Crookes. As the air is gradually removed, it is found that the dark space nearest the cathode, now known as the Crookes' dark space, gradually extends, until eventually it fills the whole tube. At this stage, green phosphorescent effects begin to appear on the anode and on the glass opposite the cathode. If a solid object, such as a screen of mica, be interposed between the glass and the cathode, a sharp shadow is seen, showing from its position that rays capable of producing phosphorescence proceed in straight lines from the cathode. These cathode rays possess energy, for a light windmill placed in their path can be made to rotate; moreover, they

are deflected by a magnet, in the same direction as would be negatively electrified particles, travelling in the course of the rays. For this reason, Crookes and other English observers from the first contended that the cathode rays were to be regarded as a flight of negatively electrified material particles; while, on the contrary, it was believed for some time in Germany, where many experiments were also made, that the cathode rays, like those of ordinary light, were of the nature of æthereal waves.

In the year 1895, Professor Röntgen of Munich made the first of the sensational discoveries in physical science for which the last few years have been remarkable. Many other recent investigations have been as interesting, and several have more profoundly modified our outlook on Nature, but few have struck so readily the imagination of the plain man as the revelation of the skeleton within the living flesh.

The origin of this discovery may be said to have been almost accidental. Röntgen noticed that photographic plates, kept under cover in the neighbourhood of a highly exhausted tube through which electric discharges were passing, became fogged, as though they had been exposed to light. He investigated this effect, and found that, when cathode rays impinged either on the glass of the

tube, or on the anode, or on any metallic plate within the tube, a type of radiation was produced which would penetrate many substances opaque to ordinary light. Dense bodies, like metal or bone, absorbed the rays more fully than did lighter materials, such as leather or flesh, and Röntgen, at once putting this discovery to some purpose, was able to photograph the coins in his purse and the bones in his hand.

Given the rays, the mechanical contrivances required to demonstrate their effects are not elaborate. Röntgen rays produce phosphorescence on screens of barium platino-cyanide and other similar salts, and, by using these screens in place of a photographic plate, objects, usually hidden from our eyes, may be made visible.

A remarkable property of the rays is their power of converting the air and other gases through which they pass into conductors of electricity. In ordinary circumstances, as was pointed out in the earlier part of this chapter, air is an almost perfect insulator; and an electrified body exposed to it, while shielded from other sources of leakage, loses its charge with extreme slowness. If, however, Röntgen rays are passing through the air in the neighbourhood of the electrified body, the charge quickly disappears.

For several years after their discovery, the

physical nature of the Röntgen rays was widely discussed, and, for a long time, no general consensus of opinion was reached. Their photographic effects and the fluorescence they produced on suitable screens suggested that, like ordinary light, they were to be regarded as waves in the luminiferous æther. The power they possess of penetrating some opaque substances does not forbid such an assumption ; for a difference in the wave-length, or in the period of vibration, is sufficient to produce marked differences in the penetration of ordinary light. Glass, transparent to the visible rays, is opaque to those invisible rays of longer wave-length, which possess great heating power—hence its use in fire-screens ; while a solution of iodine in bisulphide of carbon is opaque to luminous radiation, but allows the long waves to pass.

Röntgen rays are not refracted like ordinary light, and very little trace of regular reflection has been detected. Moreover, it is only just recently, with great difficulty, that they have been found to show signs of such a typical property as polarisation. Two plates of tourmaline seem to be as transparent to the rays when the axes of the crystals are crossed as when the axes are parallel. Such indications as these seem to be inconsistent with the identity in nature between Röntgen rays and ordinary light.

On the other hand, the rays suffer no deviation when acted on by a magnetic or by an electric field of force, a result which indicates that they are not projected particles carrying electric charges. In this particular, they must carefully be distinguished from their creative agency—from the flight of negative particles or cathode rays which, by impact on glass or metal, give rise to this new type of radiation.

In the year 1896, Sir George Stokes suggested that an explanation should be sought in the hypothesis that Röntgen rays were single pulses travelling through the æther. Ordinary light is to be represented as a series of regular waves, succeeding each other at periodic intervals, many thousand waves, almost exactly similar to each other, following in order in a minute fraction of a second. According to this view, Röntgen rays must be regarded as single disturbances, propagated with the same velocity as light, but not followed by a train of waves. The thickness of the pulse, in which the whole disturbance is concentrated, is considerably smaller than the wave-length of any visible light.

On Maxwell's theory, now universally accepted, light is explained as a series of electro-magnetic waves; and we must therefore imagine the Röntgen pulses to be electro-magnetic also. But, as

we have said, Röntgen rays are produced when a cathode ray strikes a solid object; and, if we take the cathode rays to be streams of electrified particles, it may be shown that electro-magnetic pulses will be started by their impact.

Let us examine the electric properties of these moving particles by means of the conception of tubes of force, a conception which we owe to the instinctive insight of Faraday. A small electrified body, carrying, let us suppose, a negative charge, is well known to attract other bodies in the neighbourhood when those bodies are positively electrified, and to repel them if their charges be negative. The forces which the first—the negatively electrified—body exerts may be represented by a series of lines, drawn everywhere so as to lie in the direction of the force on a positively electrified particle.

The distribution of these electric lines of force can be investigated theoretically, the laws of force being known, but it is not easy to illustrate them experimentally. On the other hand, the corresponding magnetic lines can be rendered visible and mapped out by a familiar experiment, which, indeed, first suggested to Faraday his conception of lines or tubes of force. If the poles of a horse-shoe magnet be placed beneath a sheet of

cardboard, over which iron filings are sprinkled, a picture of the magnetic lines of force is formed by the filings (Fig. 29). Under the influence of the magnetic field, each filing becomes a little magnet, and attracts others, forming chains of filings which lie everywhere in the direction of

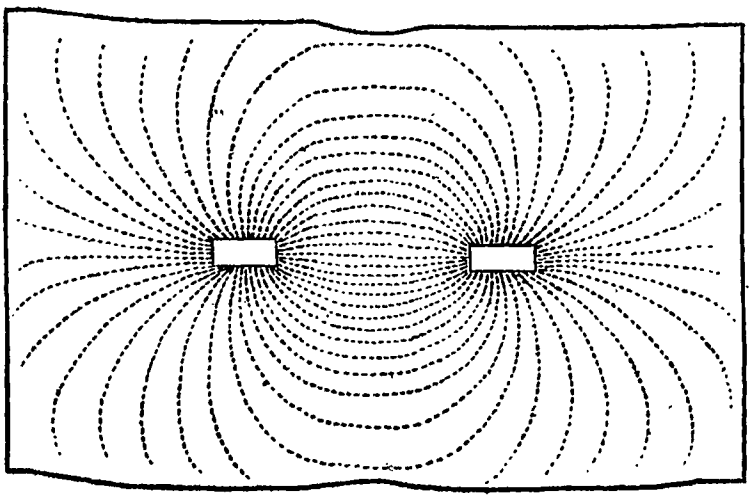


FIG. 29.

the magnetic force. Where the force is strong, the filings cluster thickly; where the force is weak few filings are to be seen. Thus a complete representation of the lines of magnetic force is obtained.

The laws of force are of the same form for electric charges as for magnetic poles, and

the filings in Fig. 30 represent also the direction and distribution of the electric lines or tubes of force in the neighbourhood of two electric charges of opposite signs. Here we have two charges; but, for an isolated charged body, the lines of electric force must evidently be radial, as shown in the region near the particle O in Fig. 30, when O*p* represents one such line of force proceeding from the electric charge at O. If the electrified particle be travelling forwards, in the direction of the arrow, it carries its lines of force with it; and, unless the particle be moving with a velocity very nearly equal to the velocity of light, the distribution of the lines is unaltered; they still are uniformly placed radii, proceeding from the particle as centre. It was predicted by Maxwell, and has been experimentally demonstrated by Rowland, Pender, and others, that a moving charged body behaves as a current of electricity. A current produces

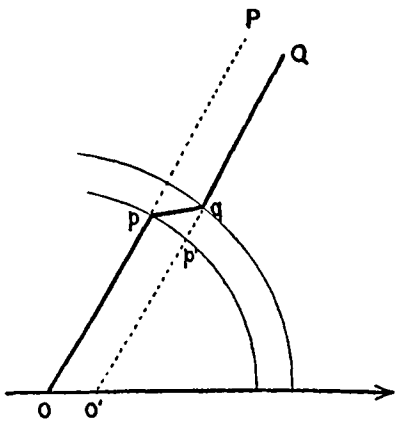



FIG. 30.

a magnetic force, and thus a magnetic field is produced by the moving particle O of Fig. 30. In this way we see that whenever electric tubes of force are moving, there exists a magnetic force at right angles, both to their length and to their direction of motion.

Now let us imagine the moving particle to be stopped suddenly. If a change could be propagated instantaneously throughout all space, the lines of force would at once stop also. But a change in electro-magnetic properties can only be propagated with the speed of an electro-magnetic wave, that is, with the velocity of light. Thus, when a moving electrified particle is arrested suddenly, a pulse of electro-magnetic force starts from the particle as its centre, and spreads out in circles, rectifying the distribution of the lines of force as it goes. The effect is shown in Fig. 30. If the particle had not been stopped, at the end of an interval of time, $t$, it would have reached some new position O', and the lines of force would be radii from this point as centre. Beyond the sphere reached by the rectifying pulse, the lines of force will still be moving parallel to $Ox$, and, at the instant considered, will be radii of the point O', while behind the spherical pulse the lines will be at rest, and will be radii of the point at

which the particle is stopped. The lines of force must be continuous; and therefore, in the pulse itself, the lines must run in some direction such as $Pq$ in the figure. The electric force near $Pq$ has then a component at right angles to the direction of propagation of the disturbance, that is, at right angles to the radial lines. Whenever a Faraday tube of electric force moves, it produces a magnetic force at right angles both to its length and to its direction of motion, and thus the line of force $Pq$ within the pulse produces a magnetic force at right angles to the plane of the paper. Now the waves of light, and, to pass to much greater wave-lengths, the waves used in wireless telegraphy, are æthereal waves of electro-magnetic force so arranged that the electric and magnetic forces are at right angles to each other, and both at right angles to the direction of propagation of the waves. It follows that the pulse, indicated by our figure as spreading out, consequent on its arrest, from a moving electrified particle, is a pulse of the same nature as the waves of light, with this exception, that, instead of a series of regular periodic waves, it consists of a single expanding shell of electro-magnetic force. Compared even with the minute wave-length of ordinary light, the thickness of the shell is exceedingly small, and depends

on the character of the arrest; it becomes smaller the more sudden the stoppage of the particle. Electro-magnetic pulses then will arise in the circumstances which are known to exist when Röntgen rays appear, and Stokes has shown theoretically that such pulses will possess many of the properties characteristic of Röntgen rays.

The successful explanation of the production and properties of Röntgen rays is strong evidence in favour of that view of cathode rays which regards them as negatively electrified particles, shot out with great velocity from the neighbourhood of the cathode. But much other evidence tending in the same direction has come to light, and nowadays no one doubts the material nature of cathode rays.

Direct evidence of the negative charge carried by the cathode rays was given by experiments of Perrin. He showed that when the rays were deflected by a magnet so that they fell on an insulated metal cylinder connected with an electrometer, a strong negative electrification was imparted to the system. When the rays fell on other parts of the bulb, this electrification was not observed.

A less direct but more interesting method is due to J. J. Thomson. In the glass apparatus

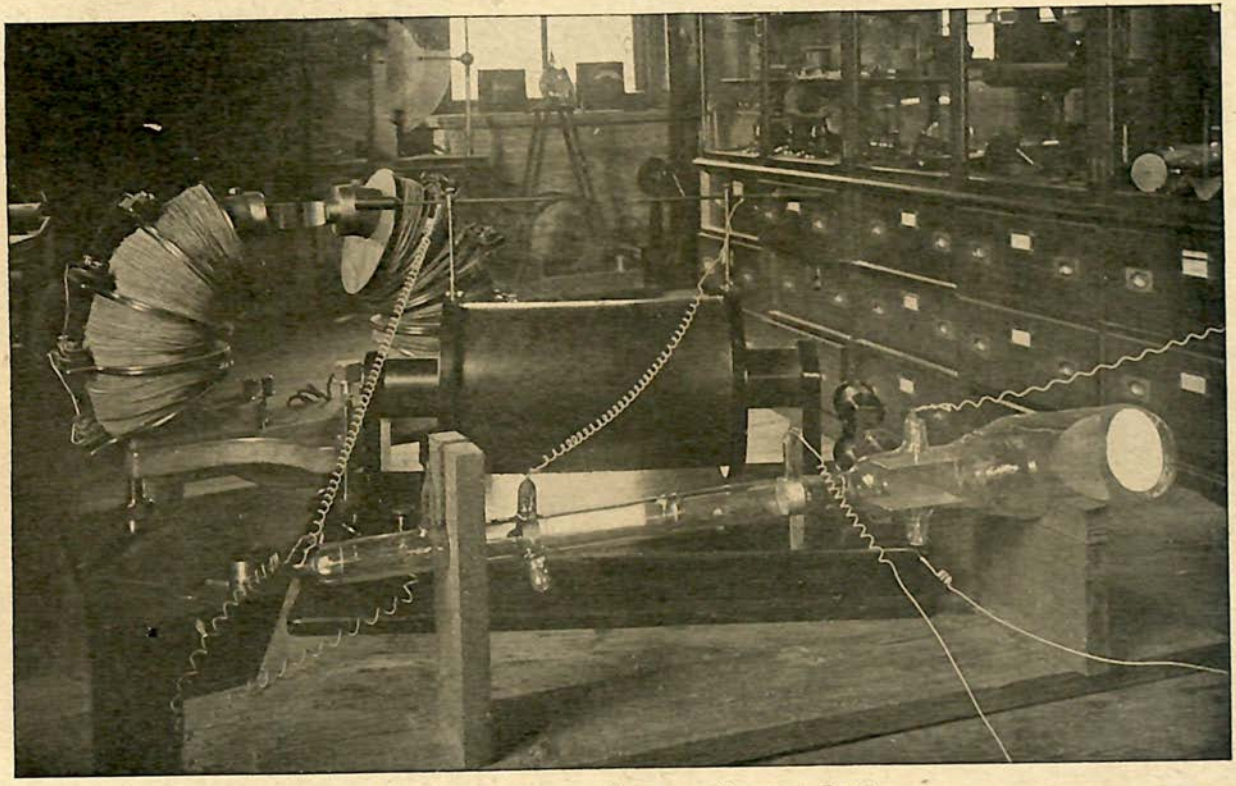


FIG. 31.—DEFLECTION-TUBE FOR CATHODE RAYS

(*Professor J. J. Thomson*)

*To face page* 173

shown in Fig. 31, which is a photograph of the tube actually used in the experiment, the left-hand terminal of the induction coil is connected with the cathode, the right-hand terminal with a thick metallic disc which acts as the anode. Through the anode, and through a second thick disc connected with the earth by the wire going to the bottom of the photograph, are bored in sequence two holes about a millimetre in diameter. A thin pencil of cathode rays is thus obtained beyond the second disc. These rays then pass between the two metallic plates, seen in the wider part of the tube, which can be connected with the poles of a voltaic battery by means of the wires passing to the right. An electric force of known amount can thus be applied to the cathode rays. When that force is sufficient, the path of the rays is deflected, and the magnitude of this effect can be determined by observing the deflection of the spot of fluorescent light at the right-hand end of the apparatus. It is well known that the cathode rays are also deflected by a magnetic field, and this effect too can be measured in the same apparatus. Both these deflections are to be expected if the rays consist of moving electrified particles; and the directions of the deflections are such that the electrification must be that to which is conventionally given

the negative sign. No system of æthereal waves yet described would give these results.

The conclusions drawn from the results of these experiments are of extreme importance. In analysing the deflections of the particles three things are involved: (1) the velocity; (2) the mass; and (3) the electric charge. For both deflections, the electric and magnetic, the two last quantities appear as the ratio $e/m$—that is, the charge divided by the mass. If we treat this ratio as a single quantity, we find ourselves with two unknown values to be determined by the two experiments, the one on the magnetic, and the other on the electric disturbances. Both the unknown quantities—to wit, the velocity and the ratio $e/m$—can therefore be found from the results of the experiments.

When a magnetic force is applied, the spot of phosphorescent light in the tube of Fig. 31 is drawn out into a band of appreciable length. This result is a consequence of a difference in velocity of the rays: in any one discharge, rays are found with a considerable range of velocity, and therefore are deflected, according to their velocities, through a series of different angles.

The following table gives some of the results of Professor Thomson's experiments, and shows the mean values of the velocity, $v$, in centimetres per second, and of the ratio $m/e$ for cathode rays, $m$

being expressed in grammes, and $e$ in electro-magnetic units of electricity.

| *Gas.* | *v.* | *m/e.* |
|---|---|---|
| Air . . . . | $2.8 \times 10^9$ | $1.2 \times 10^{-7}$ |
| Hydrogen . . . | $2.5 \times 10^9$ | $1.5 \times 10^{-7}$ |
| Carbonic acid . . | $2.2 \times 10^9$ | $1.5 \times 10^{-7}$ |

Thus, within the limits of experimental error, the results are independent of the nature of the residual gas left in the vacuum tube. Moreover, in these experiments, and in a further series due to H. A. Wilson, the results were shown to be the same whatever metal was used to form the cathode. In all circumstances the mean velocity is very high, being about one-twelfth that of light, and the mean value of $m/e$ is $1.3 \times 10^{-7}$, which makes the reciprocal ratio $e/m$ about $7.7 \times 10^6$.

Now in liquid electrolytes, the passage of one electro-magnetic unit of electricity evolves $10^{-4}$ gramme of hydrogen. Thus, in this case, the ratio $e/m$ is about $10^4$, or from seven to eight hundred times less than its value for the negative particle in a cathode ray.

But, as we have already seen (p. 157), by an application of C. T. R. Wilson's beautiful experiments on the electric formation of clouds, Thomson has proved that the individual charge on all the gaseous ions examined is the same as the charge on the ions in liquid electrolysis. Although the

cathode ray particles themselves could not be investigated in this way, there seems no reason to suppose that they are exceptions to an otherwise universal rule. If then, $e$ is the same both for gases and for liquids, $m$ must be different ; it must be from seven hundred to a thousand times less for the cathode ray particle than for the hydrogen atom.

There is another way of performing the same calculation which may be of interest in this connection. The charge on a ion is (p. 160) about $3.4 \times 10^{-10}$ electro-static units, a number which must be divided by the velocity of light, $3 \times 10^{10}$ centimetres per second, if we wish to convert it into electro-magnetic units. The result is $1.1 \times 10^{-20}$, as the value of $e$. But $e/m$ is about $7.7 \times 10^{6}$, and thus $m$, the mass of the corpuscle, is about $\frac{1}{7} \times 10^{-26}$ gramme.

The kinetic theory of gases enables us to estimate the number of molecules in a cubic centimetre of gas as about $2 \times 10^{19}$ or $10^{20}$. The number of atoms of hydrogen will be double the number of molecules ; and, as a mean value, we may take $10^{20}$ to be about the number of atoms in a cubic centimetre. This volume of hydrogen weighs $9 \times 10^{-5}$ gramme, which makes the mass of a single atom about $9 \times 10^{-23}$ gramme. Comparing this with $\frac{1}{7} \times 10^{-26}$, the mass of the

corpuscle, we again find that the corpuscle has a mass of about the eight-hundredth part of that of the atom of hydrogen.

Similar values have been obtained for the mass of the negative particles when produced in other ways. In one case, that of the ions due to the incidence at a low pressure of ultra-violet light on metals, both $e$ and $e/m$ have been measured for the same particles. A zinc plate is illuminated with ultra-violet light, and placed opposite to and parallel with a second metallic plate connected with an electrometer, the gas surrounding the apparatus being exhausted to a very low pressure. An electric force is established between the two plates, and the negative ions, produced at the zinc plate, are by this force urged towards the second plate. If no other agency were at work, all the negative ions would reach the second plate, and transfer their charges to the electrometer. Now let us imagine that a magnetic force is applied at right angles to the electric force and parallel to the planes of the plates. The magnetic force will deflect the negative particles from their original straight course, and their path becomes a cycloid. They travel out from the zinc plate, curve round, and approach it again. If the second plate is placed near enough to the first to intercept this curved orbit, all the ions will

still reach the plate connected with the electrometer and the rate at which it gains negative electricity will not be affected by the presence of the magnetic field. If, however, the electrometer plate be moved away from the zinc plate till it lies beyond the path of the ions, it will receive none of them, and the establishment of the magnetic force should completely stop the supply of negative electricity to the electrometer. If $X$ be the electric force and $H$ the magnetic force, theory shows that no ions should cross the space between the plates if the distance between them exceeds $2Xm/eH^2$, while below that distance the addition of the magnetic force $H$ should produce no effect on the rate of gain of negative charge by the electrometer.

The experiments which Thomson carried out by this method showed that no such sudden change could be produced. As the distance was diminished, or the magnetic field increased, at first the effect of putting on or taking off the magnetic force was small. Then a stage is reached at which a considerable effect is produced; while finally, in a third stage, the magnetic force cuts off almost all the ions from the electrometer plate. This somewhat gradual change is explained if we suppose that the negative ions are not all formed at the surface of the

zinc plate, but that, as the primary ions there produced move forward under the action of the electric force, they produce new ions by their collisions with the molecules of the gas. The ions are thus formed, not exclusively at the surface of the plate, but throughout a thin layer of gas near the plate. This secondary production of ions by primary ions moving with high velocities occurs in many other cases, and has been studied systematically by Townsend. It explains the large currents which can be carried by the electric arc or spark discharge.

These considerations indicate that, in the experiments we are now describing, the limit of the second stage, in which some but not all of the negative ions are stopped by the magnetic field, gives the distance at which those ions coming from the surface of the zinc plate just fail to get across the space between the plates. The expression given above then leads directly to a value for $e/m$, the ratio of the ionic charge to the ionic mass. Thomson found as the result $7.3 \times 10^6$, a number which agrees extremely well with that deduced for cathode rays, namely, $7.7 \times 10^6$.

With the negative ions produced by the incidence of ultra-violet light on a zinc plate, it is easy to repeat C. T. R. Wilson's experiments on the formation of clouds round ions as nuclei, and thus

to determine the value of $e$, the electric charge associated with the same ions for which $e/m$ has already been obtained. The result shows that, as always, the charge is the same as the charge on an ion in liquid electrolytes ; and therefore for the ions due to ultra-violet light, as for the cathode ray particles, the mass must be about the seven or eight-hundredth part of the mass of the hydrogen atom. The result has been confirmed by Lenard, who used a somewhat different type of apparatus.

In all these investigations the existence of particles much smaller than the smallest of the hitherto indissoluble chemical atoms is clearly indicated. Since the beginning of the nineteenth century the chemical atom has been the ultimate unit in which our conception of matter has been expressed. The sixty, seventy, or eighty different elements, progressively known to the chemist, seemed to be essentially different in kind, though certain likenesses between them, and periodic relations between their properties and masses, vaguely pointed to a common origin. Now, after a hundred years of usefulness, the atom yields place to Professor Thomson's corpuscle ; while the new phenomena of radio-activity, as we shall see hereafter, have shaken the belief in the immutability of the elements, and are leading to a new faith in the transmutation of matter.

Speculation, it is true, from the days of Democritus to those of Sir William Crookes, has been busy with imaginings anent ultimate particles, which should be common to all types of matter, and should compose the different elements by differences in their number or arrangement. But Professor Thomson has not followed the facile and barren paths of speculation. He has first found the particles, and has weighed and timed them before theorising on their origin and destiny.

We are now in a position to estimate the importance of the experiments which have shown that the mass of the corpuscle is independent both of the nature of the gas in which it is found, and also of the material of the electrode used in producing it. Not only must we conceive atoms to be made up of these more minute particles, but it is necessary to suppose that in all atoms, whatever be their nature, these particles are similar. The dream of an ultimate particle, common to all kinds of matter, has thus at length come true.

Further evidence is not wanting in support of this hypothesis. The absorption of ordinary light by different substances bears no relation to the density of the absorbing medium. Heavy materials like iron or glass, light bodies such as cork or water, may be either opaque or transparent. On the other hand, in the absorption of cathode

rays, and of the corresponding rays which, as we shall see, are emitted by radio-active bodies, very different phenomena appear. A given thickness of any material, whether gas, liquid, or solid, absorbs these rays simply in proportion to its mass, entirely independently of any other property. Throughout an enormous range of density, various substances, including air, the heavy gas sulphur dioxide, paper, glass, silver, and gold, possess absorption coefficients directly proportional to their densities. This remarkable relation is explained at once by the theory we are considering. If each atom of matter be composed of a number of corpuscles, and these corpuscles be extremely minute compared with the atom as a whole, it is clear that we must regard an atom as an open structure in which the vacant spaces are immense compared with the size of the tiny particles scattered throughout the atomic system under the controlling influence of their mutual forces. A collection of such atoms, forming, let us say, a thin plate of aluminium, might be quite impervious to other atoms as wholes—it might, in fact, be quite air-tight. The flight of isolated corpuscles in a cathode ray, however, if travelling fast, might be able to penetrate the plate here and there, the corpuscles finding their way between the atoms, or through the inter-corpuscular spaces in the struc-

ture of the atoms themselves. The corpuscles being all similar to each other, the relative densities of two substances, such as aluminium and air, must depend simply on the relative numbers of corpuscles which make up the atoms contained in unit volume of each material. The power, possessed by different kinds of matter, of stopping cathode rays, will also simply depend on the number of such corpuscles contained in unit volume of the different absorbing media, for the particles in the rays will readily pass through the open structure of the atomic systems, but will be stopped by collision with the substance of the individual corpuscles which make up those systems. The absorbing powers must thus, on our theory, as well as in fact, be proportional to the density of the material, and independent of all its other properties.

The relation between the corpuscles and the electric charges associated with them must next be considered. These particles have never been observed with positive charges; positive ions are usually found to have masses about equal to those of the chemical atoms. The facts may provisionally be explained by the hypothesis that the corpuscle constitutes the isolated negative unit of electricity, of which, under the name of an electron, the hypothetical existence and properties

have been studied by Professor Larmor and other mathematicians. An atom of ordinary matter, with one corpuscle beyond its proper number, is an atom negatively electrified; an atom with the corpuscle detached from it is an atom positively electrified. These charged atoms act as ions, negative and positive respectively, in accordance with the usual convention about signs.

Speculation has gone even farther than this. A moving electrified body acts like an electric current, and, as we have seen, is associated with electro-magnetic energy and electro-magnetic momentum in the surrounding dielectric medium. To change the velocity, therefore, requires the expenditure of electro-magnetic energy, and thus the electrified body possesses electric inertia in addition to its ordinary dynamical inertia. As long as the velocity is small, this electric inertia is constant, but an electrified body moving rapidly can be shown mathematically to behave as though its inertia, that is, its mass, were increased; and, as the velocity of light is approached, this apparent electric mass grows very rapidly. Some recent experiments by Kaufmann, in which the masses of the negative corpuscles emitted by radium were investigated, are of intense interest in this connection. The radium corpuscles move much more rapidly than those found in cathode rays, though

in other respects corpuscles from the two sources appear to be identical. With radium the velocities are so great that they closely approach that of light. A speed of $2.85 \times 10^{10}$ centimetres a second has been observed, that of light itself being only $3.0 \times 10^{10}$. At these enormous velocities, Kaufmann found that the value of $e/m$, determined from the magnetic and electric deflections, was considerably diminished, a value of $0.63 \times 10^{7}$ being obtained. Assuming that the charge be constant, this means an increase in $m$, the effective mass of the corpuscles.

From the theory of electrons it is possible to calculate what the increase of apparent mass should be, on the assumption that the whole of the mass of the corpuscle is an electrical manifestation, and, as we shall see in a future chapter, the results of Kaufmann's experiments agree with the calculated numbers. Such results are of fundamental importance, both physically and philosophically. It is probable that the whole of the observed mass of the corpuscle is in reality an effect due to the electro-magnetic inertia of its electric charge. Representing the atoms of ordinary matter as made up of corpuscles, and identifying the corpuscles with electrons or isolated electric charge-units, it becomes possible to explain their mass by the electro-magnetic properties

of a moving charge. To explain the phenomena of radiation, it is necessary to suppose that the electrified corpuscles—the electrons—are in rapid orbital or oscillatory motion within the atom: that, for example, the electrons whirl round in their orbits as the planets swing round the sun.

Mass or inertia is the most permanent and characteristic property of matter, and having explained mass as due to electricity in motion, the physicist may well ask the metaphysical question: has matter any objective reality; may not its very essence be but a form of disembodied energy? But then arises the further problem of the nature of electricity, and the mystery remains as great as ever, although driven one step farther back.

Instead of thus stating matter in terms of electricity, it is simpler, and perhaps less ambitious, to express electricity in terms of matter, as we have done above in saying that electrified atoms contain one or more corpuscles in excess or defect of their normal number. Nevertheless, the electron theory of matter, formerly supported on mathematical grounds, has been strengthened greatly by these recent developments of experimental science. Moreover, from the point of view of radio-activity, which we shall consider in the next chapter, that theory is of supreme importance, for, if the atom consists of electrons in rapid orbital motion, it is

possible that some corpuscles may occasionally fly away from their orbits. In a few such cases many corpuscles may depart from an atom at once, and leave the residue in an unstable state, in which the rearrangement of the remaining corpuscles into new atoms is necessary for equilibrium. Thus the electron theory suggests the occasional instability of matter. Now the occasional instability of a complex chemical atom, and its disintegration into simpler bodies, as we shall presently see, is the probable, perhaps the certain, explanation of the phenomena of radio-activity.

Among the various agencies enumerated at the beginning of this chapter for the production of gaseous ions, special interest attaches to the action of incandescent metals and carbon. Elster and Geitel, Richardson, H. A. Wilson, and others have shown that, as a platinum wire is gradually heated, it begins to emit positive ions at a temperature corresponding to a low red heat. The investigation of the influence of a magnetic force shows that these ions vary in size, some probably being molecules of the gas, and others molecules of the metal or even dust disintegrated from its surface. As the platinum is still further heated, negative ions also come off, ultimately in large excess. In vacuo the negative leak from platinum and carbon filaments is very large—from carbon it may even

amount to as much as an ampère of current from each square centimetre of surface. The negative ions are then of sub-atomic dimensions, and are identical with the corpuscles otherwise obtained. H. A. Wilson has shown that, at the lower temperatures at which the negative leak occurs, it is very largely due to the effect of hydrogen absorbed in the platinum, and liberated under the action of the heat. At the highest temperatures, however, the corpuscles due to the wire itself seem to be much more numerous than those depending on the presence of hydrogen, and to the metal itself we must then look for their source.

The emission of corpuscles at high temperatures is not confined to solids. Thomson finds that sodium vapour also gives off a large supply, and the effect seems to be common to all kinds of matter at a white heat. Carbon is particularly efficacious, perhaps because it can be raised to a higher temperature than can metals. It is easy to demonstrate the existence of a measurable current from one limb of the carbon filament of an ordinary incandescent lamp to an insulated plate placed between the limbs.

Owing to the emission of corpuscles by an incandescent wire or carbon filament along which a current flows, the effective current-carrying area of the wire is increased. In vacuo a considerable fraction of the current might pass through the

space surrounding the wire, which must become filled with corpuscles. Although in gases at ordinary pressures the emission of corpuscles is less copious, still, ionization will occur to an appreciable extent just round the wire, and a part, though perhaps a small part, of the current will pass along outside the substance of the wire.

The phenomena we are now considering must have an important bearing on cosmical processes. The photosphere of the sun contains large quantities of glowing carbon, and this carbon will emit corpuscles until the resultant positive charge left on the sun exerts an electro-static force great enough to prevent further emission. In this way a condition of equilibrium would be reached. Any local elevation of temperature would then cause a stream of corpuscles to leave the sun and pass into the surrounding space. When corpuscles pass through a gas with high velocity, they make it luminous, and Arrhenius has explained many of the periodic peculiarities of the Aurora Borealis by the supposition that corpuscles from the sun, due either to incandescence or to some other cause, stream through the upper regions of the earth's atmosphere.

The phenomena of electrolytic conduction through liquids, and of non-electrolytic conduction

through metallic substances, must now be interpreted in terms of this corpuscular theory. The chemical decomposition of electrolytic solutions, which we have described in Chapter IV., indicates that an electric transfer through such liquids involves a movement of the chemical constituents of the substance decomposed. In fact, as we have seen, that movement has been experimentally demonstrated, and the passage of the ions rendered visible. We must suppose, then, that the corpuscle forming the effective negative essence of the anion, is, in liquid electrolytes, attached to an atom of matter. This atom may possibly be associated with other atoms or molecules forming a complex ion, but the point is that the isolated corpuscle cannot slip from one atom to another, and thus carry an electric current through the liquid; the corpuscle cannot move without a corresponding movement of matter—of matter, that is, in its atomic or molecular sense.

The motion of the positive ion here again involves the simultaneous passage of a particle of matter of at least atomic dimensions. The positive ion consists of an atom of the electrolyte with one of its corpuscles missing. In this way, a unit of negative electricity is removed from it, that is, it is left with a positive charge. Electricity, on this hypothesis, is one, not two; the two

so-called opposite electricities being perhaps an excess or defect of a single thing. Thus the nomenclature of the old "one fluid theory" is still appropriate, the word fluid being understood strictly in a "Pickwickian sense." It is true that the meaning of the conventional names positive and negative should be reversed; it is the old negative electricity which, from this point of view, is the real corpuscle, and a positive charge means a deficiency in the proper number of the electrical units. But the signs conventionally attached to electric charges are a mere matter of historical accident, and the fact that fate wrongly allotted the names is in harmony with the frequent experience of us all, in cases where two alternatives are possible, and a free choice is assured.

In metals an electric current flows without chemical change in the substance of the conductor, so that, in this case, we must imagine the corpuscles to be freely mobile. They pass from atom to atom, and thus carry the current when an electromotive force acts. In the presence or absence of such a force, they may be regarded as existing within the metal in a state resembling in many ways the state of a gas in a closed vessel. Estimates have been made of the number of corpuscles present in a given volume; of the velocity with which they move under an electric

force ; and of their mean free path within the metal, that is, of the average distance a corpuscle moves between its collisions with other corpuscles. As we have seen, when the metal is heated, the corpuscles begin to leave it, and stream away into the surrounding space. At any temperature equilibrium is set up between the corpuscles leaving the metal owing to the effect of temperature, and those drawn back again by the residual positive charge on the metal. We may look on the system as analogous to a liquid in equilibrium with its own vapour.

In the last chapter we saw that it was necessary clearly to distinguish the electric current and the heating effect of the current from the flow of the energy by which the current was maintained. The energy passes through the surrounding medium, through the luminiferous æther. The current is merely the line along which the energy of the æther can be dissipated as heat. Faraday and Maxwell showed that the medium invoked to explain the phenomena of light was also competent to explain electric and magnetic manifestations. An electric force is a state of strain in the æther, and the immediate function of an electric machine or voltaic battery is to set up such a state of strain. If the poles of the battery are insulated from each other, the state

of strain is maintained, the poles are attracted towards each other with a small force, but nothing else happens. Faraday, as we have seen, represented this state of strain by drawing lines of force, or tubes of force, which map out the electric field, and everywhere follow the direction of the electric force. The tubes of electric force end on the surfaces of conductors, and the opposite ends of each tube, where they touch the conductors, are the physical meaning of unit electric charges of opposite sign. The state of strain in the field is such that we must imagine the tubes of force as tending to shorten in length and to push each other apart; and, when the poles of a battery are disconnected, the tubes of force will be in equilibrium under these forces The distribution of the electric tubes will then be very similar to that of the magnetic lines, made visible by the filings shown in Fig. 29 on page 168.

A conducting wire must be regarded as a channel along which the free ends of a line or tube of force can move, and, when the poles of the battery are connected by means of a wire, the tubes of force in the surrounding air run their opposite ends on to the wire, pull those ends towards each other, and shut up. Other tubes are then pushed into the wire by

their mutual transverse pressure, and are obliterated in turn. The tubes of force in the dielectric field are thus inclined to disappear, and the state of æthereal strain in that field tends to be relieved. Simultaneously, however, the battery endeavours to reassert the original distribution of tubes, and once more to set up the strain. In this way new tubes are constantly forming between the terminals of the battery, and are as constantly pushed into the connecting wire, where they vanish. When the connection is metallic, it is only the negative ends of the tubes, attached to the corpuscles, that move, the positive ends remain at rest. If, on the other hand, part of the circuit is composed of an electrolyte, in that part the positive ends of the tubes are also mobile. Now it is this continual process of establishment of æthereal strain by a battery, and the compensating process of its obliteration along a conductor that, according to the views of Faraday and Maxwell, now universally adopted, constitute an electric current.

The ionic theory of electrolysis gave a clear idea of the mechanism by which the slipping of the ends of the tubes of force occurred in conducting liquids, and now the corpuscular hypothesis gives us an equally vivid insight into the

nature of the process within metallic circuits. The tubes, anchored by their ends to an ion in electrolytes or to a corpuscle in metals, drag their anchors. It is the slip of the anchors that constitutes the current, and the heat developed by the passage of the current is to be explained by the frictional resistance to the drag of the anchor, or to some other means of dissipating energy, such as inter-corpuscular radiation, not yet fully understood.

Faraday had no skill in mathematical analysis, and his insight into physical principles is one of the best examples of scientific instinct found in history. As was well said by Von Helmholtz in the Faraday Lecture for the year 1881, "Now that the mathematical interpretation of Faraday's conceptions regarding the nature of electric and magnetic forces has been given by Clerk Maxwell, we see how great a degree of exactness and precision was really hidden behind the words, which to Faraday's contemporaries appeared either vague or obscure; and it is in the highest degree astonishing to see what a large number of general theorems, the mathematical deduction of which requires the highest powers of mathematical analysis, he formed by a kind of intuition, with the security of instinct, without the help of a single mathematical formula. I have no intention

of blaming his contemporaries, for I confess that many times I have myself sat hopelessly looking upon some paragraph of Faraday's descriptions of lines of force, or of the galvanic current being an axis of power."

Such a confession from a man of the commanding ability of Von Helmholtz shows how far the instinctive genius of Faraday had carried him in advance of his age. "We must also in his case acquiesce in the fact that the greatest benefactors of mankind usually do not obtain a full reward during their lifetime, and that new ideas need the more time for gaining general assent the more really original they are, and the more power they have to change the broad path of human knowledge."

# CHAPTER VI

## RADIO-ACTIVITY

"To watch the abysm-birth of elements."
—KEATS, *Endymion*.

SCIENTIFIC investigation, which usually proceeds unmarked by most of those not directly engaged in it, is from time to time forced on the attention of the public by some discovery of immediate and striking advantage to mankind, or by the attainment of some theoretical result, which, from its novelty and interest, fires the imagination of every thinking man.

To those who follow closely the course of research, these brilliant advances in knowledge rarely come suddenly. The slow and patient work of many observers through long years often leads up to and suggests the particular step from which follows, almost of necessity, the practical application or the far-reaching theory. The mathematical genius of Clerk Maxwell, the experimental skill of Hertz, laid the foundations on which, some years afterwards, was reared the superstructure of wireless telegraphy. The observations of Crookes,

Lenard, J. J. Thomson, and many others, on electric discharges through rarified gases, had given to the physicist an extended insight into the nature of these phenomena, before Röntgen's almost accidental discovery—that photographically active rays thus obtained could traverse certain substances opaque to light—revealed the bones in his hand to the man in the street.

General attention has lately been directed to the subject of radio-activity. M. Curie demonstrated that the stream of energy constantly proceeding from the newly-discovered element radium could be detected by a measurable rise of temperature in a small quantity of the substance protected from loss of heat; and the publication of this result was followed by a correspondence in the *Times*, in which some surprising efforts were made to explain the source of the energy, and to elucidate the "mystery of radium."

In this case also the essential phenomena have been under investigation longer than is generally known; and their detection naturally arose from a knowledge of the properties of Röntgen rays. These rays produce fluorescent effects on suitable screens; and it was natural to examine phosphorescent and fluorescent substances, to determine if they were the source of similar radiation. For some time no definite results were obtained; but,

in the year 1896, M. Henri Becquerel discovered that compounds of the metal uranium, whether phosphorescent or not, affected a photographic plate through an opaque covering of black paper, and rendered the air in their neighbourhood a conductor of electricity.

Such were the first observations on the property of radio-activity; but the rapid development of the subject which has followed could only have taken place with the aid of our previous knowledge of the electrical properties of gases. Although the superficial similarity between Becquerel rays and Röntgen rays has proved for the most part misleading, the relations between the two branches of the subject are so intimate that it is impossible to study satisfactorily the phenomena of radio-activity without a knowledge of the results previously and simultaneously reached by the investigation of electric discharge through gases.

After Becquerel's discovery of the photographic and electric activity of uranium, it was found that, like Röntgen rays, the rays from uranium produced electric conductivity in air and other gases through which they passed. In the year 1900, M. and Mme. Curie made a systematic search for similar properties in a great number of chemical elements and compounds, and in

many natural minerals. They found that several minerals containing uranium were more active than that metal itself. Pitch-blende, for instance, a substance consisting chiefly of an oxide of uranium, but containing also traces of many other metals, was especially active. When obtained from Cornwall its activity was about equal to that of the same weight of uranium, but samples from the Austrian mines were found to be three or four times as effective. The presence of some more active constituent was thus suggested. To examine this point, the various components of pitch-blende were separated chemically from each other and their radio-activities determined. In this way three different substances, radium, polonium, and actinium, all previously unknown, appear to have been isolated by different observers. Of these three the most active is the now well-known radium, discovered by M. and Mme. Curie, working with M. Bémont.

Radium is obtained from pitch-blende in company with the metal barium ; and the two seemed at first to be connected chemically so intimately that the new substance was for a time called "active barium." However, a slight difference in the solubilities of some of their salts enables them to be gradually separated by a process of repeated fractionisation, the radium chloride and bromide

crystallising out more readily than the corresponding compounds of barium.

These processes of chemical separation are remarkable for their use of the new property of radio-activity as a sole guide in the operations. After each reaction the activities of both the product and the residue were determined. It was thus settled whether the reaction just tried was effective, and in which of the substances separated by the reaction the property of radio-activity had been concentrated.

The quantity of radium present in pitch-blende is extremely small, many tons of the mineral yielding, after long and tedious work, only a small fraction of a gramme of an impure salt of radium. Its extraction is consequently a matter of great labour and high cost. Radium salts of fair purity have now become articles of commerce, at all events in Germany, though the supply is usually insufficient to meet the demand; and radium is at present worth many thousand times its weight in gold.

An interesting point in these investigations is the extreme sensitiveness of the property of radio-activity as a test for the presence of those substances which possess it. A delicate electroscope will easily show a leak of electricity with a substance having an activity of about the one

hundredth part of that possessed by uranium. The activity of pure radium has been estimated as about one million times that of uranium; and such radium is a definite, well-marked chemical element, like other elements, forming salts and other chemical compounds, and giving strong bright lines when heated and examined with a spectroscope. Spectrum analysis has hitherto been the most delicate means at our disposal for detecting the presence of the chemical elements; but in the preparation of radium from pitch-blende its spectrum only began to appear when, in the prolonged process of fractionisation, the product had reached an activity of about fifty times that of uranium.

It appears from these figures that the electroscopic method of detecting radio-active matter is several thousand times more sensitive than the most refined methods of spectrum analysis, and in other cases a still greater sensitiveness seems to have been reached. History has again repeated itself. When the spectroscope was first placed in the hands of chemists, it revealed the existence of several elements which occurred in quantities too small to be detected by any other means then known. In a similar way additional elements have now been detected and isolated by the help of the newer and more powerful method of research,

In the year 1899 Professor Rutherford of Montreal, one of the band of physicists trained by Professor J. J. Thomson at Cambridge, discovered that the radiation from uranium consists of two distinct parts. One part was found to be unable to pass through more than about four layers of thin aluminium foil, while the other part would pass through about one hundred layers before its intensity was reduced by one half. The first named, or $\alpha$ rays, produce the most marked electric effects, while the more penetrating, or $\beta$ rays, are those which affect a photographic plate through opaque screens. At a later date was detected a third type of still more penetrating radiation, known as $\gamma$ rays, which can traverse plates of lead a centimetre thick, and still produce photographs and discharge electroscopes. In proportion to its general activity, radium evolves all three types of radiation much more freely than uranium, and is best employed for their investigation.

The moderately penetrating, or $\beta$ rays, can easily be deflected by a magnet; and Becquerel, who deflected them by an electric field as well, conclusively proved that they were projected particles, charged with electricity. M. and Mme. Curie had shown previously by direct experiment the existence of a negative charge associated with

these rays. Owing to their ionizing action, it is impossible to demonstrate that a body surrounded by air gains a charge when exposed to the rays. Such a charge would leak away as fast as it was acquired. But by working in a very good vacuum, or by surrounding the body with a solid dielectric such as paraffin, the acquisition of a negative charge can be demonstrated by means of an electrometer. Further investigation showed that the $\beta$ rays behave in all respects like cathode rays, although they possess greater velocities than any cathode rays hitherto examined, velocities which have different values ranging from 60 to 95 per cent. of the velocity of light. The $\beta$ rays, then, are negative corpuscles, or negative electrons.

Magnetic and electric fields which are strong enough to deflect considerably the $\beta$ rays, produce no effect on the easily absorbed $\alpha$ rays. Although Strutt, in the year 1900, had suggested that the $\alpha$ rays were positively charged particles, of mass greater than that of the particles which constitute the negative $\beta$ rays, it was not till some time afterwards that their magnetic and electric deviations were experimentally demonstrated, and shown to be in the direction opposite to that observed with $\beta$ rays. The mass of the carriers in the $\alpha$ rays appeared to be about that of helium atoms—more

than one thousand times greater than that of the negative corpuscles—but evidence is now accumulating which casts some doubt on this result. The velocity is about one-tenth of that of light. The very penetrating or $\gamma$ rays have never been deflected, and from this evidence it has been supposed that they are different in kind to the other types, and, like the X rays discovered by Röntgen, consist of wave-pulses travelling through the æther with the velocity of light. On the analogy of the cathode rays, we should expect that such pulses would be started as a secondary effect of the $\beta$ rays; but, in August 1903, Strutt published experiments which show that, as with the $\alpha$ and $\beta$ rays, and also with the cathode rays, different gases absorb the $\gamma$ rays in direct proportion to the density. Such results were in favour of the view which regards the $\gamma$ rays as particles of some kind travelling at speeds exceeding those of the other rays, and perhaps carrying no electric charges, for the absorption phenomena exhibited by ordinary Röntgen rays are of an entirely different kind. But further evidence has just appeared. In March 1904 it was announced by Mr. A. S. Eve and by Mr. R. K. M'Clung that very "hard" Röntgen rays—that is, the thin and intense electro-magnetic pulses produced by the cathode rays of very high

vacua—show absorption phenomena similar to those of the $\gamma$ rays of radium. Forasmuch, as the $\beta$ rays travel with velocities higher than those of any ordinary cathode rays, we should naturally expect the resulting pulses to be thinner and more intense than ordinary Röntgen rays. It seems clear, therefore, that $\gamma$ rays are identical in origin and character with very "hard" Röntgen rays.

All the three types of radiation, when they pass through air or any other gas, render the gas a conductor of electricity, so that the charge of an electroscope or of an electrometer leaks away. The charged particles of doubtful mass which constitute the $\alpha$ rays, the negative corpuscles or electrons which form the $\beta$ rays, and the intense electro-magnetic pulses of the $\gamma$ rays are all able to convert some of the molecules of a gas into electrified ions. The $\alpha$ and $\beta$ projectiles probably effect this change by the energy of their collisions with the molecules of gas, and it is possible to estimate the number of ions produced by each shot. It has been reckoned that this number is sufficient to give air a measurable conductivity when one positive particle per second is emitted by the radio-active substance. Even if one atom of radium emits only one such particle, this estimate means that the electroscope is

able to detect effects which depend on one atom coming into action each second. We may well be astonished at the delicacy of this means of research.

Again, all three kinds of rays produce phosphorescent and photographic effects, though the penetrating power of the $\beta$ and $\gamma$ rays makes the phenomena due to them more remarkable.

Radium salts are self-luminous, owing either to the direct emission of light by their agitated atoms, or to some phosphorescent effect of the internal bombardment produced by their radio-activity. The spectrum of this spontaneous luminosity has been photographed by Sir William and Lady Huggins, and was shown to correspond with the spectrum obtained by passing electric sparks through nitrogen. Sir William Crookes and Professor Dewar found that this spectrum vanished when the radium compound was placed in a high vacuum. Probably, therefore, it is due to the effect of the activity of the radium on atmospheric nitrogen surrounding the radium salt or occluded within it.

A screen of the phosphorescent substance, zinc sulphide, when placed in the neighbourhood of a radium compound, glows brightly, and Crookes has used this property in a most striking and beautiful experiment. A tiny fragment of a radium

salt is fixed at the distance of a fraction of a millimetre in front of a plate covered with zinc sulphide. On looking through a lens or a low-power microscope in a dark room, brilliant scintillations are seen, and the splash of the atomic projectiles of the α radiation as they strike the target is thus made visible to the human eye. It seems probable that each scintillation is immediately due to a cleavage of one of the tiny crystals of zinc sulphide under the influence of the bombardment.

In the year 1900 Rutherford made another striking discovery. The radiation from thorium was known to be very capricious, being affected especially by slight currents of air passing over the surface of the active material. Rutherford traced this effect to the emission of a substance which behaved like a heavy gas having temporary radio-active properties. This emanation, as it was named, is to be distinguished clearly from the radiations previously described, which travel in straight lines with velocities approaching that of light. The emanation diffuses slowly through the atmosphere, as would the vapour of a volatile liquid. It acts as an independent source of straight line radiations, but suffers a decay of activity with time.

Similar emanations are given off by radium

and actinium, but not by polonium or uranium. The emanations seem to be very inert chemically, in this resembling gases of the argon group. They pass unchanged through acids or hot tubes, but are condensed at the temperature of liquid air, evaporating again as the tube is warmed. By taking advantage of this property many pretty lecture-room experiments may be performed. For example, a quantity of radium emanation is condensed in a tube surrounded with liquid air. The tube is connected with others, and, if the liquid air be removed, the emanation can be traced as it diffuses, by the fluorescence it excites on the glass, or on small pieces of paper covered with zinc sulphide, which are placed here and there within the tubes. By measuring the rates of diffusion of the emanations into other gases, their densities have been approximately determined and found to be about one hundred times that of hydrogen.

When the emanations come into contact with solid bodies, they cause these bodies themselves to become temporarily radio-active. This excited or induced radio-activity, which is found to be acquired more readily by negatively electrified surfaces, is apparently due to radio-active positively electrified particles clinging to the surfaces. Whatever the effective substance may be, it, or

the matrix in which it is deposited, can be dissolved in some acids and regained as a radio-active residue on evaporation.

All the three types of radiation considered above, and known as $\alpha$, $\beta$, $\gamma$ rays, have one remarkable property which, at first sight, is not shared by the emanations just described. The radio-activity of any element, with regard to the emission of these rays, is independent of the compound in which that element is contained. Thus, for a mass containing the same amount of the element radium, the activity of radium chloride is the same as that of radium bromide; while uranium, the metal, has the same activity as it has when chemically combined in uranium nitrate. Moreover, an alteration in the physical conditions, such as temperature, which always largely influence the course of ordinary physical and chemical changes, seems, throughout an extended range, to be entirely without effect on the processes involved in radio-activity. Heating to redness, or exposure to the extreme cold of liquid air, equally leave the activities we are considering untouched. Pursuing these investigations to even lower temperatures, M. Curie, during a visit to England in the summer of 1903, took advantage of the resources of the Royal Institution to examine the properties of

radium when exposed to the temperature of liquid hydrogen. Professor Dewar's calorimeters then indicated that the heat produced by 0.7 gramme of a salt of radium was somewhat greater than at higher temperatures; at any rate, it was not less. In liquid hydrogen most chemical activities are entirely suspended, and the result obtained by M. Curie and Professor Dewar, to whatever cause it may be due, is very remarkable. Whether or not the increase they then noted be confirmed by further experiments, it seems certain that, till we thus approach the absolute zero, all the activities of radium are quite independent of temperature. Such extraordinary results as these point to a deep-seated difference in kind between the radio-active processes and all chemical and physical operations hitherto investigated. We shall presently examine this point more closely.

Unlike the "straight line" radiations of the types $\alpha$, $\beta$, and $\gamma$, the emanations discovered by Professor Rutherford are emitted much more freely from some compounds of the radio-active element than from others, while the rate of emission is largely dependent on physical conditions, such as the temperature of the system. By a striking series of experiments, however, Rutherford has traced these differences to varia-

tions in the ease with which, after formation, the emanation escapes from the generating substance.

Let us consider these results in more detail. It is found, for example, that while the emanation is given off very slowly from dry and solid radium chloride, it is freely emitted from the same salt in solution. This allows the problem to be submitted to the test of quantitative experiment. The rate of decay of the radium emanation is known; its activity falls to half value in 3.7 days. Thus, the activity of the emanation stored in a solid radium salt reaches a limit, when its rate of decay becomes equal to the constant rate at which the emanation is produced by the radium. On the hypotheses that the emanation is formed at the same rate in the solid as in the solution, that it escapes from the solution as fast as it is formed, and that it does not appreciably escape from the solid at all, it is clearly possible to calculate the amount of emanation that should be stored in the solid, as compared with the amount produced and emitted by the solution in a given time.

The calculation shows that 463,000 times more should be stored in the solid than is emitted by the solution in one second. Now if, as supposed, the emanation is stored in the solid, this large amount will be liberated instantaneously when

that solid is dissolved in water. Rutherford and Soddy measured this rush of emanation by its effect on an electroscope, and found that it was 477,000 times greater than the quantity afterwards developed by the solution in one second: a remarkable confirmation of the several hypotheses given above.

The effect of raising the temperature is similar to that of solution. When a solid radium compound is brought to a red heat, a rush of emanation takes place, which makes the initial emanating power some hundred thousand times greater than that of the cold solid. This high rate of emission, however, does not last; it, also, is due to the rapid escape of stored material.

By experiments such as these, the emanating power of radio-active elements has been brought into line with their other radio-active properties, and has been shown to depend only on the mass of the element present, whatever be the state of combination in which that element exists, and whatever be the physical conditions under which the process occurs.

Soon after appreciable quantities of radium were available for investigation, Giesel drew attention to the fact that a radium compound gradually increases in activity after formation, and

only reaches a constant state after a month's interval. Similar phenomena have been observed by Curie and Dewar for the heat effect. These results are readily explained if we consider the properties of the emanation as elucidated by the experimental evidence that has now accumulated.

When a salt of radium is dissolved in water, and the solution boiled, the emanation previously stored in the salt is evolved and removed. The residual activity of the salt is then found to be much diminished. This activity must include that due to the radium itself, and also the excited activity, which has been developed by the emanation, but is not removed with it. The effect of the excited activity decays rapidly; after a few hours it will nearly have vanished, and we then get the true activity of the pure radium salt alone, uncomplicated by that of the emanation, or by the excited activity which is produced by the emanation.

This residual, non-separable activity is found to consist entirely of $\alpha$ rays, and, measured electrically, is about 25 per cent. of the normal activity of a radium compound after a month's existence; a normal activity which comprises the combined effects of radium, of the radium emanation, and of the excited activity.

Rutherford and Soddy studied these relations

in detail. They dissolved a radium compound, removed the emanation, and waited till the excited activity had subsided. The solution was then evaporated, and the recovery of the activity of the solid crystals of salt was traced by measuring at intervals the ionizing power. The results are shown in Fig. 32, where, neglecting the residual

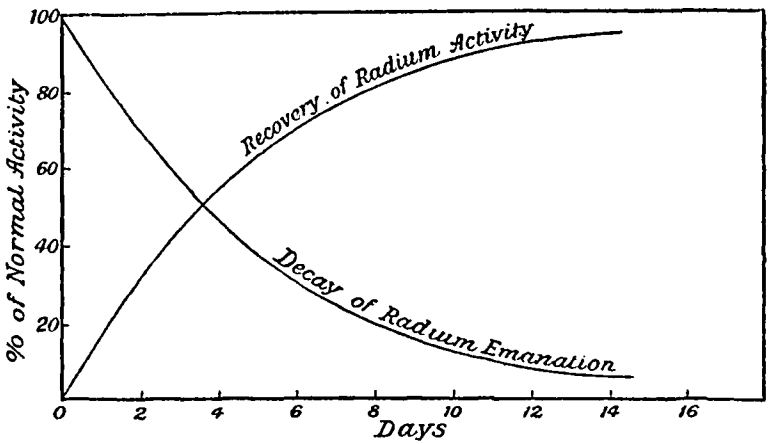



FIG. 32.

activity, the recovery curve of the activity of the salt is compared with the curve of decay of activity of the separated emanation. It will be seen that the two curves are complementary to each other ; the activity of the emanation falls to half its initial value in a little less than four days, and the purified radium salt recovers half its final activity in the same time. If the ac-

tivity of the emanations at any instant be added to that of the recovering radium, the result is equal to the normal activity of the radium when fully recovered. Thus the total activity of the residual radium and its separated emanation, considered together, remains constant throughout, though resolved into constituent portions. This result again illustrates the characteristic feature of radio-active processes: the impossibility of changing the amount of activity by any known chemical or physical operations.

Since the phenomena of radio-activity have been well known, and the various types of radiation and emanation which proceed from radio-active materials clearly distinguished, traces of the property have been found to be disseminated very widely. Mr C. T. R. Wilson, for example, has detected radio-activity in newly-fallen rain and snow; when evaporated they leave a residue which discharges an electroscope. Professor J. J. Thomson has found that when air is bubbled through various samples of water from deep wells, or when the water is boiled and the dissolved air driven off and collected, there is present in the air a radio-active gas, which behaves as though it were the emanation from some active substance of which slight traces are con-

tained in the water. The air loses its active properties, while the water regains a small part, and after some days will again yield a supply of active gas. The rate of recovery and decay seem to be about the same as for the radium emanation, and this suggests that the active material is radium in minute quantity.

Again, McLennan, Rutherford and Cooke, and Strutt have found that the rate of leak in a closed vessel depends on the nature of the walls of the vessel. Strutt even detected differences with different samples of the same material. Cooke diminished the rate of leak in a brass electroscope by carefully cleaning the walls. Probably this result is to be explained by the presence of slight traces of some active emanation in the atmosphere, and the consequent excited activity on solid materials. The excited activity is removed by cleaning, but the fact that it seems to be impossible to prevent some ionization of the air, indicates the possibility that ordinary materials are faintly radio-active.

Evidence pointing to a similar conclusion has been obtained by Thomson, who finds that by surrounding an electroscope with thick layers of different substances, the leak of electricity may be increased or diminished but never quite destroyed. The materials themselves seem to

emit radiations which partly compensate the absorption they exercise on the radiation from surrounding objects. On the other hand, boiling many finely divided substances in water failed to produce any trace of emanation. According to the evidence at present available, it seems probable that, while all bodies are to some slight extent radio-active and emit ionizing radiations, emanations are emitted only by a very limited number of elements.

The air of the atmosphere itself, when tested with a sensitive electroscope, is found to possess a slight conductivity. It seems likely that this effect is due to traces of some radio-active substance, whence issue the radiations which ionize the air. The rate of leak of electricity through air has been shown by Elster and Geitel to be greater in a cave or cellar than in the open; while air drawn from a clay soil contained a radio-active emanation. From such experiments we know that traces of some radio-active substance are present in many places in the earth, and we know that some active bodies emit radiations of extremely penetrating nature. It thus seems reasonable to believe that the slight conductivity which appears to exist at all times in the atmosphere is due to the production of gaseous ions by the action of stray

radiations proceeding from some radio-active material, near or far.

Radium seemed at one time destined to play a useful part in the future curative treatment of certain diseases. Röntgen rays have occasionally been employed as a means of checking the spread of cancer, and the radiations from radium also appeared to be effective, besides being applied far more easily locally, and for considerable periods. Unfortunately the existence of such benefits remains doubtful.

The medicinal springs of Bath and Buxton contain radio-active emanations, while radium itself has been detected in the solid deposits at Bath. It is possible that the curative effects of these waters is caused by their radio-activity, and if so, the uselessness of drinking the water, when kept and removed to a distance, may be due, more to the decay of the activity of the emanations, than to the provident imagination of the local authorities.

Mr. Soddy has suggested that inhaling the emanations of radium, or, preferably, of thorium, might prove a useful way of treating lung disease. The gentle radio-activity thus obtained is perfectly under control by varying the time of application ; and the excited activity on the walls of the lungs would continue the treatment in a milder form for

some hours after the inhalation had ceased. For surgical purposes also, radium, if it could be prepared fairly pure in moderate quantities, would be more convenient than Röntgen rays, for the production of which complicated and expensive apparatus is needed, apparatus, too, somewhat capricious in its action.

At the same time it is clear that the use of radium is attended with difficulty and danger. When kept near the skin it causes sores, of a nature not yet fully understood, which only appear some days afterwards, while if caterpillars or other little animals are confined in a box with a small quantity of a radium compound, they die in a few hours.

In seeking an explanation of these physiological effects, recent experiments, due to Mr. W. B. Hardy, must be noticed. As we have seen in Chapter IV., solutions of salts and acids, which are conductors of electricity, possess the power of coagulating clear solutions of colloidal or jelly-like substances such as albumen or sulphide of arsenic, and this action is readily explained by referring the coagulative action to the electric charges on the ions.

The influence of charged ions on colloidal solutions being thus made clear, Hardy tried the effect of exposing a very sensitive solution of

globulin, a substance contained in the living tissue of animals, to the charged particles emitted from radium, which so readily produce ions when passing through a gas. The penetrating $\beta$ rays were without action, but the easily absorbed $\alpha$ rays, which enter a film of the liquid when it is placed near a radium salt with no screen interposed, immediately coagulated the globulin. On the other hand, the $\beta$ and $\gamma$ rays were found to induce certain chemical reactions, liberating iodine from iodoform in presence of oxygen. This change is also produced by ordinary light and by Röntgen rays, but not by the $\alpha$ radiation. These results, physical and chemical, may explain some of the curious physiological effects of radio-active substances.

It seems unlikely that radium will ever be cheap enough for us to use its energy as a source of mechanical power, but it is just possible that the phosphorescence of sensitive screens in the neighbourhood of a radio-active body may some day act as a practical source of light. In this way luminous effects would be obtained directly from a store of energy self-contained and practically inexhaustible, whereas, in all our present arrangements, light is derived from a hot body, and large quantities of energy are necessarily wasted in maintaining the incandescence.

In order to gain some insight into the cause of radio-activity, we must now examine another series of phenomena of fundamental importance, which were discovered in the case of uranium, by Crookes and by Becquerel, and in the case of thorium by Rutherford and Soddy. By definite processes of chemical fractionisation, somewhat like those by which radium was isolated from pitch-blende, products can be obtained in minute quantities from uranium and thorium many times more active than those substances themselves. The uranium and thorium from which those products have been separated lose much of their activity; the radiation they then emit seems to be an inseparable property of the elements themselves, and is of the $\alpha$ type only. To the separated products the names of uranium-$X$ and thorium-$X$ have been given. The important point is this: if these $X$ products be kept for some weeks or months, they will be found to have lost their radio-active properties, while the original samples of uranium or thorium will have become as active as they were before the separation, and will again emit all three types of radiation. The rates at which the processes of loss and gain of activity occur have been carefully studied by Rutherford and Soddy, and shown to correspond accurately with each other. This correspondence is clearly

shown by the curves in Fig. 33, which give the decay of activity of the separated uranium-*X*, and the recovery of the residual uranium. Again we see that the total amount of activity remains constant, and is not affected by the processes of chemical action.

These experiments lead to a definite view as to

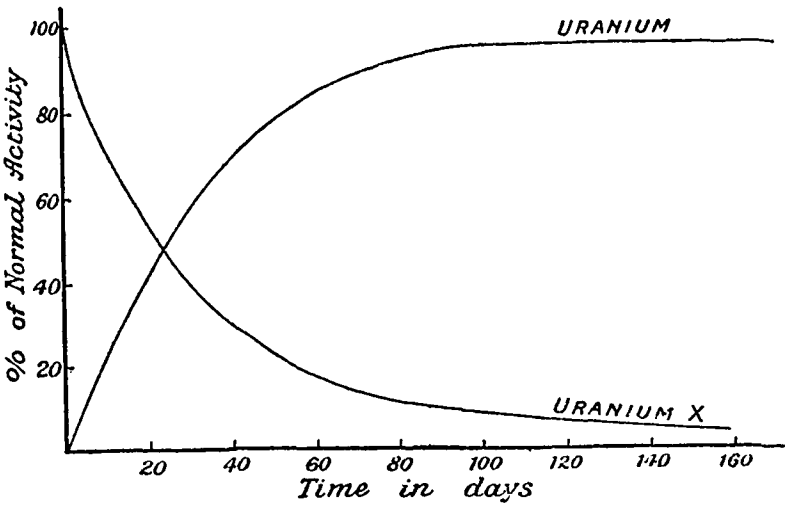



FIG. 33.

the source of the radiations. It has been suggested that the energy proceeding from radio-active bodies is obtained by drawing on some unknown radiation constantly streaming through space, a radiation which active bodies alone have the power of absorbing and re-emitting in forms capable of detec-

tion by our instruments. But the activity of a radium compound is found to be normal when the compound is kept within a thick case of lead, which would probably absorb stray radiation, and moreover, the suggested explanation ignores the results of experiments such as those just described, which show that, whenever radio-activity exists, the active material is always slowly changing into some other substance, which has distinct chemical properties, and can be separated by chemical means from the original material. Thus, in the case of thorium compounds, the radio-active body producing most of the effects usually observed is not really thorium, but a definite substance we may call thorium-*X*, which is being formed at a constant rate from the bulk of the thorium, and, after its formation, gradually loses its activity. The radio-activity of the pure thorium seems to be a consequence of its change into thorium-*X* and to accompany that change. The activity of the thorium-*X*, in a similar way, accompanies, and is a consequence of, its continual change into other bodies, in this case, the thorium emanation. The constant activity of a thorium compound, as ordinarily found, is thus due to a balance in the rate of production of the active thorium-*X* and the rate of its loss of radio-activity.

What view are we to take of the changes in the thorium or uranium which result in the formation of the *X* products, and what further changes must we suppose to go on when the *X* products give rise to emanations or radiations? Are these changes of the nature of ordinary chemical action, in which atomic or molecular combinations, or rearrangements of the atoms in a molecule, are involved, or must we look deeper for their causes?

Three essential pieces of evidence should be considered in this connection. The rate at which radio-active power is gained or lost depends only on, and is always proportional to, the total amount of active material at any instant remaining effective; it does not depend on the concentration of that material. For instance, if the activity of a quantity of thorium-*X*, or of radium emanation, be examined, it will be found to decrease during each unit of time by the same fraction of the value it had at the beginning of that interval. If, in the first four days, the activity falls to half its initial value, during the second four days it will fall to half that half-value, or to one quarter of the initial value; during each successive four days the remaining activity is halved, the process being represented by a curve of the type of those in Figs. 32, 33. The rate of decay does not depend

on the volume which the material occupies. This mode of change in a geometrical progression, depending only on the total amount of effective material present at the instant, is well known in chemical processes. In such processes it always indicates that the reaction is an alteration going on in the individual molecules, which may either be dissociating into simpler molecules, or be suffering a rearrangement of their constituent atoms. Each molecule undergoes this change alone, and does not react with other molecules. If, on the other hand, a change is going on, in which combination or rearrangement between two reacting systems is involved, whether the systems consist of atoms or molecules, another law holds; and the rate of change is found to increase when the material is concentrated into a smaller space, so that the two systems are more closely within reach of each other. In the phenomena we are considering, then, the change involves one system only, whatever that system may be.

In examining the further question thus raised, we are at once confronted with the remarkable fact that the radio-activity of a series of compounds of any radio-active element is simply proportional to the amount of the element which they contain. The activity of the element is not affected by its state of combination, or by very

great changes in the physical conditions, such as temperature, which play a large part in determining ordinary physical or chemical equilibrium. As we have seen, this remarkable result applies not only to the emission of the "rays," but also to the evolution of the emanations which proceed from some of the radio-active elements; the differences in emanating power have been traced to differences in the rate at which the emanations can escape from the various compounds under various conditions. The law of decay of activity shows that one reacting system only is involved; these further phenomena show that the system does not alter with the changing conditions which are found to affect all known molecular processes, or with the state of combination which affects the physical and chemical properties that control the behaviour of the elements in all other respects. Moreover, as we shall see later, it is possible to calculate the energy liberated by a given amount of radio-active change. This energy is at least five hundred thousand times, and may be ten million times, greater than that involved in the most energetic chemical action known.

The conclusion is thus forced on us that, in radio-active processes, we are dealing with changes in the atoms themselves, and are watch-

ing the phenomena which accompany a true transmutation of the elements. The continuity of the problems which present themselves to the human intellect is once more strikingly demonstrated, for surely the imagination must be deficient which does not see in these transformations of matter a partial fulfilment of the dreams of the mediæval alchemist.

The strength of any hypothesis lies in its power of adequately co-ordinating observed facts, and of intelligently forecasting the discoveries of the future. If, then, we accept this new revelation, and in its light reconsider the phenomena we have already discussed, we shall be able to marshal our facts in orderly array, while the few privileged pioneers alone can tell how much assistance they have already received from it in their brilliant achievements.

Let us then, in terms of this new theory, re-state the results which we have already described. All radio-active elements have very high atomic weights, the atom of radium, for instance, being about 225 times as heavy as that of hydrogen. Radio-active atoms are therefore very complex structures, and, on the theory we are considering, are capable of breaking down into simpler and lighter systems. The elements thorium and uranium contain some few atoms

which, at any moment, are disintegrating. As we have seen, the activity of the pure separated thorium or uranium consists of $\alpha$ rays only. Thus, the essential process of the radio-activity of these bodies consists in the emission of $\alpha$ rays, the disintegration of each atom resulting in the projection of one or more $\alpha$ particles with a velocity about one-twelfth that of light, while the residues break down into new and simpler atoms, which are themselves in a state of instability, and are known to us as thorium-*X* and uranium-*X*.

The further transformation of these bodies is very rapid, their activity disappearing in a time to be measured in days. It is probable, however, that in radium we possess an analogous substance, also an intermediate product in a state of instability, the life of which is enormously longer. The primary substance, standing to radium as thorium stands to thorium-*X*, is at present uncertain; it may be one of the metals which are found in pitch-blende.

As in the formation of the *X* product, the essential process in the radio-activity which accompanies its disintegration consists in the ejection of the positively charged particle which we recognise as an $\alpha$ ray by its power of ionizing a gas through which it passes, and thus

rendering that gas a conductor. The loss of this positive particle implies a change in the atomic residue, which now, in the case of uranium-*X*, seems to lose all radio-active properties, and therefore to pass out of reach of our present powers of observation.

In compounds of radium and thorium, however, we get the emanations as the next step in the process of atomic dissociation. These bodies also are unstable, that is, radio-active. They emit new $\alpha$ rays, and produce the excited activity which generally appears in a deposit on the walls of the containing vessels. This again breaks down, with the usual accompaniment of $\alpha$ radiation. The decay of the excited activity on a rod, exposed for a very short time to the radium emanation, is shown in Fig. 34. The curve is a complicated one, and may profitably be compared with the simple curves giving the rate of decay of the activity of uranium-*X*, the curve of Fig. 33 on page 223, and with the curve of decay of the radium emanation, Fig. 32 on page 215. Rutherford has shown, however, that the complex curve of the decay of the excited activity of radium can be made up by the conjunction of three constituent curves, of the usual typical form shown by uranium *X*. This indicates no less than three

successive changes in the radio-active matter: (1), a rapid initial change, accompanied by radio-activity; half the matter changes in about three minutes; (2), a slower change involving

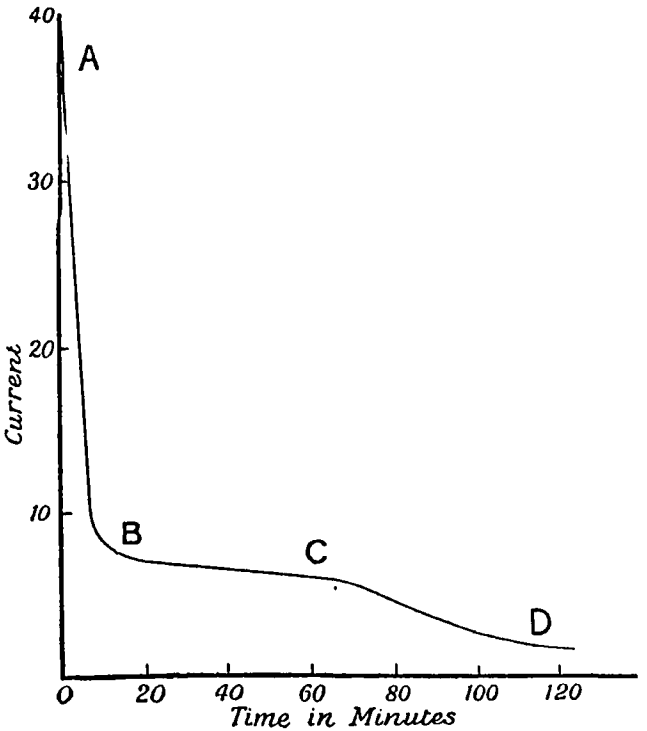



FIG. 34.

no radio-activity, in which half the substance changes in thirty-six minutes; (3), a radio-active change, half completed in about twenty-eight minutes. The actual curve is the resultant

of these three processes, which are going on simultaneously. It is remarkable that in this way we can detect and investigate an atomic change involving no radio-activity. We cannot but wonder whether some such disintegration may not be taking place in the atoms of ordinary materials, which undergo no simultaneous radio-active changes, or, at all events, none great enough to be accurately investigated in the way by which alone we can apprehend at present such non-radio-active changes.

Therefore, in all, five certain stages have been traced in the disintegration of the radium atom, as it passes successively into the emanation and the three types of matter described above.

Evidence of a still further change is also forthcoming. Surfaces exposed to the radium emanation retain about the 1/20,000 part of their initial excited activity, apparently for an indefinite period. Rutherford points out that the total amount of ionization produced by the whole process of disintegration seems to be about the same for each of the successive changes of radium which can be traced throughout its entire course. If we extend this conclusion to the persistent excited activity, it follows, since the activity at any instant is about the 1/20,000 part of that of the emanation, that the life of the

active deposit must be about 20,000 times longer than that of the emanation, which decays to half its intensity in four days. The persistent excited activity would thus half disappear in about 200 years. However that may be, we are now nearing the final stage, where the residue left by the successive changes ceases to be radio-active, and can no longer be followed by our instruments.

The quantities of matter involved in any radio-active change are excessively minute, and no other method at present known enables us to detect the final inactive products as they are formed. It is, however, not improbable that, by the slow accumulation of material which must of necessity go on when a radio-active body is kept for a long time, the inactive products will eventually be obtained in amounts sufficient to be distinguished by the spectroscope or even by ordinary chemical analysis. In this connection we must give due weight to the fact that in all radio-active minerals considerable quantities of the gas helium are occluded. Sir William Ramsay and Mr. Soddy, by spectroscopic methods, have detected the presence of helium in the gases evolved from a sample of radium, originally prepared from pitch-blende and kept as a solid for some months. The spectrum of helium was invisible when the emanation was first collected

and examined, but it soon appeared and gradually increased in intensity with the lapse of time.

Similar results have been obtained by Dewar and Curie, who, moreover, appear to have traced the disappearance of a minute volume of the emanation. This has been explained by the idea that the resulting helium, being projected in the atomic state with great velocity, penetrated the glass walls of the vessel and thus occupied no volume. The decrease in the volume of a minute quantity of emanation has also been observed recently by Ramsay and Soddy.

Such results are very suggestive: it seems difficult to avoid the conclusion that helium is one of the final products obtained by the disintegration of the radium atom. But a few years since, the inactive elements of the group containing argon and helium were revealed to us. It now seems conceivable that we are about to learn from them a secret as yet undisclosed by other elements, the secret of their origin. The density of helium, about double that of hydrogen, suggested the possibility that the $\alpha$ rays themselves consist of positively electrified helium atoms; but further evidence is needed before we can finally solve these fascinating problems of the ultimate state of extinct radio-active matter.

So far we have referred to the $\alpha$ type of radia-

tion alone, and this type seems to play the primary part in radio-active change. The $\beta$ and $\gamma$ radiations only appear when the series of atomic transformations accompanying radio-activity is nearing its completion. With uranium, $\beta$ and $\gamma$ rays are emitted only by the substance uranium-$X$, and this, since no emanation is known, must represent the last radio-active residue. With radium and thorium, the excited activity due to the emanations is the last product formed before the radio-active properties vanish; and, with these metals, this excited activity freely gives rise to the $\beta$ and $\gamma$ radiations, which are absent both from radium and thorium and also from their emanations. The emission of $\beta$ and $\gamma$ rays by a solid radium compound is due to a similar excited activity produced in the solid by the emanation which that solid is always developing and absorbing. This explains the gradual increase in activity of a radium compound for some weeks after its deposition from solution. The increase has been observed both with the electroscope and by measurement of the heat evolved. When first deposited, we get the effect of the solid radium salt, which gives $\alpha$ rays alone; but, as the emanation is gradually produced and stored in the solid, not only does the amount of $\alpha$ radiation grow greater, but $\beta$ and $\gamma$ radiations, due to the excited activity, also appear.

The nature of the $\alpha$ rays still awaits final elucidation. Their positive charges seem to be transient, and, if so, their calculated masses cannot be relied upon. They may be flights of helium atoms; but their penetrating power is much greater than that of cathode rays with equal velocity, and, as H. A. Wilson suggests, they may consist of positive electrons. The large apparent mass must then be due to the size of the radius, minute, even compared with that of the negative electron (see p. 283). This and other points remain for future investigation; but the main features of the theory we have outlined, if they cannot yet be said to be as firmly established and as widely accepted as some older physical generalisations, have at all events provided us with a consistent treatment of the subject, and constitute an effective hypothesis on the lines of which, it is safe to predict, will be continued in the coming years the researches which have already so notably widened our outlook on the workings of nature.

Such is the theory of radio-activity indicated by the remarkable series of investigations that have followed Becquerel's original discovery. We are led to refer the energy liberated to transformations in the chemical atoms, and to recognise clearly, what has long been suspected, that the store of

energy in the atoms themselves enormously transcends the energy involved in ordinary physical or chemical changes, in which the atoms suffer no alteration. This internal atomic energy, then, must be looked on as the source of the heat experimentally detected by Curie in the neighbourhood of a radium compound. Its immediate cause may be, partly at least, the internal bombardment of the $\alpha$ particles, which, shot off by the radium and the emanation stored in it, are for the most part absorbed by the substance itself. Rutherford has traced the increase of the heat effect in radium bromide newly precipitated from solution, and has shown that it grows *pari passu* with the radio-activity as measured electrically—a method which, as we have seen, depends chiefly on the $\alpha$ radiation.

The greater part of the radiation coming from a solid radium compound is emitted by the stored emanation and its product, the excited activity. The emanation can be extracted only in such minute quantities that, except in most exceptional conditions, its radio-activity alone reveals to us its existence. As we have seen, the emanation is of the nature of a dense gas, half of any quantity of which would be transformed into other substances in about four days. Owing to this process of change, only a limited

amount of emanation could be obtained from a given quantity of radium, and the bubble which could be evolved from the small supply of radium possessed by any experimenter would be too minute to be visible, except by the most refined and sensitive methods of investigation. Could a cubic inch of the radium emanation be obtained, the radiation from it would be so powerful that the vessel used to contain the gas would, in all probability, be fused instantly.

By the methods we have already described, it is possible to determine the mass and the velocity of the projected particles, and therefore to calculate their kinetic energy. From the principles of the molecular theory, we know that the number of atoms in a gramme of a solid material is about $10^{20}$. Four or five successive stages in the disintegration of radium have been recognised; and, on the assumption that each of these involves the emission of only one particle, the total energy of radiation which one gramme of radium could furnish if entirely disintegrated seems to be enough to raise the temperature of $10^8$ grammes, or about 100 tons of water, through one degree C. This is an under-estimate; it is possible that it should be increased ten or a hundred times. As a mean value, we may say that, in mechanical units, the energy available for radiation in one ounce of

radium is sufficient to raise a weight of something like ten thousand tons one mile high.

An interesting problem then arises for solution. From Curie's determination of the heat evolved, or from estimates of the number of ions produced by each $\alpha$ particle as it flies through air till its energy is absorbed, we may calculate approximately the energy radiated in a given time. Hence we deduce the possibility of estimating the rate at which the observed radiations of a piece of radium would decrease—that is, the length of life of radium as its atoms, one after another, undergo disintegration. On the minimum estimate we have given, Rutherford calculates the life of radium as a few thousand years; and, although it is probable that this is less than the truth, it seems that a gramme of the material would so diminish in the course of a few hundred thousand years, that the activity of the residue would cease to be a measurable quantity. The activity of uranium and thorium is so much smaller than that of radium that their lives must be perhaps a million times longer, and the amount of matter disintegrated in a year a million times less. We are thus again impressed with the exceeding delicacy of our measurements of radio-activity, by which we can detect in a few seconds the results of changes to be demonstrated by the balance only after the lapse of many thousand years.

Forasmuch as the life of radium is less than the probable age of the minerals in which it is found, we may surmise that the element is continually formed by the disintegration of other atoms. If this be so, the radio-activity of uranium minerals will reach a constant value when the rate of formation of radium is equal to its rate of decay. Radium is found only in association with ores of uranium, and in amount roughly proportional to the quantity of uranium present. A suspicion thus arises about the parentage of radium. As far as is known, uranium undergoes only one change in which $\alpha$ rays are emitted, while four such changes have been detected in radium. The rates of formation and decay being the same, it would seem that, when radio-active equilibrium is reached, the activity of the mineral should be about four times that of uranium. It is remarkable that, allowing for traces of other active elements such as thorium, this is about the actual value of the activity of the best pitch-blende.

It will now be clear that, on the theory which has been put forward, we are, while investigating a radio-active body, in reality watching the process of the evolution of matter. Radio-active substances, themselves unstable, may have been formed by the disintegration of parent atoms,

which are unknown to us, and, indeed, may now be non-existent on our globe. Radio-activity denoting an unstable state, it is probable that the total amount of it in the world is constantly diminishing, as the atoms of the active elements gradually pass into inactive forms. Perhaps in former ages nearly all matter was intensely radio-active; and mankind has discovered these phenomena only in the last cosmical moments of a few thousand or million years before they cease for ever to manifest their existence in the striking manner which has made radium so remarkable.

When we trace in this way the creation and evolution of new elements, it is impossible to resist wondering whether the process of change, so far observed to an appreciable extent only in a few radio-active bodies, may not in reality be a general property of matter, though in other cases possessed in such an infinitesimal degree that it almost transcends the delicate means of detection that are now at our disposal. As we have seen, experimental evidence is not altogether wanting in favour of such a supposition. We must, at any rate, cease to regard matter as essentially eternal and unalterable; the possibility of its undergoing a continual though slow process of evolution is clearly before us.

A striking property of radio-active change is our inability to produce it, or even to modify its course, by any of the powerful means within the resources of modern physical science. The highest temperature we can employ, the intense cold of liquid air, are equally useless. The observation that the activity of radium is independent of the concentration of the material shows that the disintegration of one part of the substance is not accelerated by the radiation from another part. Even under the fierce and continuous bombardment of the atomic projectiles hurled forth by radium, and the sharp musketry of its corpuscular $\beta$ rays, the residual atoms are unaffected. They remain unchanged by the action of any external agency, till, in the fulness of time, their own internal processes result in instability, and from the shattered fragments of each radium atom, as, in its turn, it breaks asunder, new elements emerge.

By investigating radio-active changes, we can trace the transmutation of the elements; we can watch the evolution of matter; but we have not yet found the philosopher's stone which brings these processes under our control. It would be rash to predict that our impotence will last for ever, but at present there are no signs of its removal. Still, strange things happen nowadays, and yet stranger things may be seen by future

generations. It is conceivable that some means may one day be found for inducing radio-active change in elements which are not normally subject to it. Professor Rutherford has playfully suggested to the writer the disquieting idea that, could a proper detonator be discovered, an explosive wave of atomic disintegration might be started through all matter which would transmute the whole mass of the globe, and leave but a wrack of helium behind. Such a speculation is, of course, only a nightmare dream of the scientific imagination, but it serves to show the illimitable avenues of thought opened up by the study of radio-activity.


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## CHAPTER VII

### ATOMS AND ÆTHER

"Oh, dear! what can the matter be?"
—*Old Song.*

OUR primary conception of matter as continuous in time and space fails to correspond with phenomena which are perceived as soon as inquiry passes beyond the most elementary stages. The expansion of a quantity of gas without assignable limit can hardly be represented mentally if the gas is thought of as a homogeneous substance completely filling the space in which it exists. We cannot imagine that the same amount of substance fills equally at different times volumes different from each other. The immediate difficulty disappears if we suppose the gas to consist of a number of discrete particles, which can be pressed nearer together or allowed to move farther apart.

The phenomena of diffusion, too, clearly indicate that liquids and gases must consist of particles in motion relatively to each other, capable of pene-

trating the interspaces between the similar particles of contiguous bodies. A vessel filled with hydrogen and a vessel filled with oxygen, when opened into each other, soon contain an equal mixture of the two gases, while two solutions in contact gradually become of uniform concentration throughout. Nor are such processes confined to fluids. Sir William Roberts-Austen has shown that gold, if placed in intimate contact with lead, will diffuse at ordinary temperatures to such an extent that, after the lapse of some years, it can be detected in the lead by chemical analysis at distances of a millimetre or more from the surface of contact. Chemical analysis is by no means one of the most sensitive methods of research, and to be discovered in this way the gold must have migrated to a considerable extent.

Again, all our present conceptions of the nature of heat rest on the view that it is a form of energy —the energy of agitation of particles too small to be recognised or controlled individually by ordinary mechanical means. No hypothesis previously proposed offers any approach to a satisfactory explanation.

While the most obvious phenomena thus point consistently to the conception of the grained structure of matter, the more recondite branches of physical science indicate the same conclusion by

evidence which, in its cumulative effect, is irresistible. The phenomena of liquid electrolysis, no less than those of gaseous discharge and radioactivity, have been successfully co-ordinated and explained by ionic hypotheses which are an extreme form of molecular theory. Indeed, in the experiments devised by C. T. R. Wilson, the clouds deposited on ionic nuclei seem, by no very violent stretch of the imagination, to bring the individual ions themselves within reach of our imperfect senses, and Crookes has shown that the molecular bombardment of the individual $\alpha$ particles from radium may possibly be rendered visible by the scintillations produced on a fluorescent screen of zinc sulphide.

Turning to chemistry, we are again impelled to molecular conceptions by the familiar evidence on which rests Dalton's atomic theory. It is true that here the possibility of an alternative explanation, based on the principles of energetics alone, is now before us. Mixtures possessing a maximum or minimum melting or boiling-point change their state without change in composition of either phase. The particular composition at which this mode of change occurs depends in general on the physical conditions, such as pressure. If, however, as a limiting case, variation in conditions is without effect, the system would be classed as a com-

pound or an element—a compound if the constancy extends only over a limited range, an element if no known variation of conditions will alter the composition. Whether or not the need for atomic conceptions may thus be banished from chemistry, such conceptions must still remain as an alternative explanation.

Truth may possess many aspects, and provisionally we may accept safely the idea of the molecular structure of matter. It remains to consider whether it is possible to obtain any exact knowledge of the dimensions of this structure, that is, of the number of molecules we must suppose to exist in a cubic centimetre, and of the size of the molecular individuals.

It is clear that the molecules must be at least as small as the most minute piece of matter we can prepare and recognise, and in many ways it is possible to obtain substances in a very fine state of division. Gold leaf can be beaten out till its thickness does not exceed the millionth part of an inch, while the deep blue colour of thin smoke coming from a wood fire shows that the particles therein are able to distinguish selectively the various waves making up a beam of white light, and must therefore be comparable in minuteness with the lengths of those waves.

Such results as these, while fixing an upper limit to the size of molecules, are powerless to assist in the determination of a lower limit, smaller than which the inter-molecular distances cannot be. Such inferior limits can, however, be determined, and to one of the methods by which they have been obtained — one due to Lord Kelvin — we will now turn.

A soap bubble always tends to contract and diminish its area, and therefore, in order to increase its size, it is necessary to do work against the force of contraction to an amount which may be calculated by measuring the surface tension of the film. Adding the energy required to prevent the film from cooling during its extension, we can calculate the total work absorbed per unit increase of area. By continual extension it would be possible to expend an unlimited quantity of work, as long as no change in the nature of the film took place under the influence of the progressive expansion and consequent attenuation of the film. The point at which it is natural to expect that some change would occur is that moment when the two sides of the film have been brought so near to each other, by the process of continual thinning, that the outside faces confining the film come within range of each other's molecular forces. But, however far the film be extended, it is evident

that, as long as it remains a film, less work must be used than could otherwise be expended in evaporating the film and converting its substance into steam, since by this means its molecules would be separated completely from each other's sphere of influence. The value of this latter amount of work is known from other experiments, and is the latent heat of evaporation of the substance of the film, which is composed almost entirely of water. It is possible, therefore, to calculate for the film a hypothetical thickness, certainly less than the critical thickness at which it would begin to show new properties owing to the approach of the opposite faces within molecular distances. Numerical results show that this limiting thickness may be put at about $10^{-8}$ of a centimetre. There are thus not more than ten million molecules in a row in a length of a millimetre, and two hundred million in the space of an inch. The numbers in the corresponding volumes will be found by cubing these values; a cubic centimetre of water contains not more than $10^{24}$ molecules. This, as we have indicated, is a maximum estimate; it is possible that the number is less.

As already suggested, the interdiffusion of gases also leads to a molecular conception of their structure, and from the observed values of the coefficients of diffusion, and of the allied property,

viscosity, it is possible, from the principles of the kinetic theory, to calculate more exactly the number of molecules in a cubic centimetre of a gas. The results of the investigation indicate about $2.5 \times 10^{19}$ molecules per cubic centimetre. Since water, the liquid, is about 1200 times denser than its vapour, it follows that a cubic centimetre of water contains about $3 \times 10^{22}$ molecules, a number which may profitably be compared with the maximum estimate given above. Such figures do indeed convey little to the mind; but it may be useful to remember that the thinnest line clearly visible in a good microscope—a line with a thickness approaching the hundred-thousandth of a centimetre — would need about three hundred molecules to stretch across it from side to side. Thus the molecular structure of matter is not immeasurably finer than magnitudes which, with the aid of modern instruments, our senses are enabled to apprehend.

Our mental picture of matter, then, is that of a discontinuous substance; we can, moreover, form some notion of the number of grains in a given volume, and we know some of the chemical properties of the individual grains. But what is the nature of these particles? Are they similar in kind to the matter-in-bulk they com-

pose, or do the properties of matter-in-bulk appear as a consequence of the collaboration of vast numbers of particles essentially different in nature from any lump of matter we can touch or see? Again, are the particles which make up different kinds of matter different from each other, or has all matter a common constituent? Are the different elements composed of identical particles of which the number and arrangement form the determining factors of the chemical atoms?

Such questions have puzzled mankind from early times, and, until theories began to be founded on facts and tested by experiment, the track of history is strewn with the speculative hypotheses of the metaphysicians and the poets. Here and there a lucky guess or shrewd suggestion chances to agree with the views which represent, temporarily it may be, the conclusions of experimental science. It is curious and interesting that, to many highly educated people, the problems connected with the constitution of matter are better known by such triumphant proofs of the sagacity and scientific insight of some Greek philosopher than from the more definite conceptions tentatively put forward by a Kelvin, a Larmor, or a J. J. Thomson, from the basis of experimental knowledge.

The problems at issue could not even be formulated profitably till the work of Dalton and Avogadro had fixed our ideas of atoms and molecules. In the light of present knowledge, we define an atom to be the smallest particle of matter which can take part in chemical action, or enter into the chemical structure of a compound. It is the ultimate chemical unit; anything smaller than an atom, if such a particle is to be found, would have no chemical properties, and it would play no distinguishable part in ordinary chemical action. The atom is, moreover, defined as the unit of the chemical elements. An atom of a compound is a meaningless term; the atoms of water, for instance, would be, not water, but hydrogen and oxygen.

As to the outward chemical nature of atoms, *quâ* atoms, physics has nothing to say; but molecules, on the other hand, may be regarded either from a chemical or from a physical aspect. Chemically they are the ultimate units of the compound, the smallest parts of that compound which can exist and still retain the properties of the compound. Any farther subdivision would result in the liberation of the elements. Physically, on the other hand, molecules are the smallest particles of matter which act as wholes in the incessant irregular move-

ments which the particles of matter are always undergoing. The energy of these molecular movements is the energy of heat; and in the most striking case, that of a gas, the impact of the molecules on the walls of the containing vessel gives the physical explanation of the pressure which the gas exerts. It is evident that the physical molecule may contain one or more chemical atoms. Clear evidence shows that in well-known gases such as oxygen and hydrogen, the molecule consists of two atoms, while the vapours of some metals, mercury, for example, possess monatomic molecules.

Thus the relations between atoms and molecules are ascertained, and further inquiry must deal with the intimate structure of the atom, as the more fundamental unit.

The essence of Dalton's great discovery was that the relative chemical combining weights of the different elements lead directly to a knowledge of the relative weights of the atoms of those elements. Since Dalton's time it has been recognised that the atoms, in the chemical sense of the word, of different elements must have different weights and different properties. If, then, we look for some common constituent composing the different elementary substances known to chemistry, we must look within the

atom; we must cease to regard it as the ultimate unit, and examine the internal structure of the atom itself; we must abandon the etymological meaning of the word, retaining it only for its historic associations.

On arranging the elements in order of their atomic weights, Mendeleef discovered that periodic relations become apparent between the physical and chemical properties, elements with similar properties recurring at constant intervals. This periodicity was so marked a feature that it was possible to arrange the elements in groups, in which the various properties were possessed by the individual members to a greater or less extent, according to their position in the groups. It was even possible successfully to predict the atomic weight, properties, and compounds of undiscovered elements from knowledge of the behaviour of their neighbours, which were situated round empty spaces in the periodic table.

The periodic law suggests a common origin for the elements, and indicates that, as we pass from light to heavy atoms, we are going from simple to complex structures containing different numbers of some common sub-atom. The atomic weights of many elements are nearly simple multiples of that of hydrogen, and Prout supposed that hydrogen was the ultimate basis from which

other elements took their rise. Accurate experiments have not eliminated the small divergence of several atomic weights from whole numbers, and Prout's hypothesis in its original form has long been discarded; but the idea of some common constituent in the different elements has much evidence in its favour, and only waited for definite experimental confirmation to be received as the natural conclusion of many promising speculations.

For the first time, in 1897, such definite experimental evidence was given by Professor J. J. Thomson, who, in the remarkable series of researches described on pages 172 to 180, clearly showed that, in the cathode rays of a vacuum tube, we can detect corpuscles possessing about one-thousandth part of the mass of the lightest atom known to chemistry, that of hydrogen. These corpuscles were shown to be identical, whatever the nature of the residual gas in the tube, and whatever the metal employed as electrode. The corpuscles are common to all kinds of matter, and the mind at once sees in them the long-sought ultimate basis from which all atoms are made.

To explain the phenomena of radiation, and all the complex systems of lines which appear in the spectra of the elements, it is necessary

to imagine these corpuscles, not locked together in a close-packed conglomerate, but moving in oscillatory or orbital motion under the influence of their mutual forces. The emission of corpuscles from the radio-active elements also indicates such movement, for it is unlikely that the high velocities with which the corpuscles are hurled away should have been impressed on them at the instant of ejection.

Thomson has published recently (March 1904) a mathematical investigation of the conditions of stability of systems of revolving corpuscles, and has thereby deduced in a most remarkable manner many of the properties of the different chemical atoms. He supposes any one atom to consist of a uniform sphere of positive electrification, the structure of which is not specified, and of a number of negatively charged corpuscles revolving in orbits within that positive sphere, under the influence of the attraction of the positive electricity and of their own mutual repulsions.

A similar problem was long ago attacked by Mayer by means of experiment. A number of little magnetised needles were thrust through corks, and were allowed to float on the surface of water with their axes vertical. The similar poles of all the magnets were directed upwards,

and thus the resultant force between the magnets was a repulsion. High above the water was placed a powerful bar magnet, with that pole downwards of which the magnetisation was opposite in kind to that of the upward poles of the little floating magnets. This large pole attracted inwards all the little poles pointing upward, and thus the magnets were drawn towards the centre by the attraction of the big magnet suspended above them, and at the same time were repelled from the centre by their mutual repulsions. Under the influence of these two forces they assumed positions of equilibrium.

Mayer found that as long as the number of little magnets was not more than five, they arranged themselves in a single ring, but that, on increasing the number to six, a discontinuity of arrangement was observed, the single-ring structure ceased to be stable, and the magnets placed themselves with five in a ring and one at the centre. This two-ring configuration persisted as more magnets were added, till the number rose to fourteen, with five in the middle ring and nine in the outer circle. With fifteen magnets this arrangement in its turn became unstable, and a three-ring system appeared.

Thomson has now overcome the difficulties of

the mathematical analysis, and has shown that similar phenomena of disposition must appear in the system which, as described above, he imagines may correspond with the atom. Here also, discontinuities in arrangement will appear, and, when certain definite numbers of corpuscles have come together, an additional ring will be formed. Periodic likenesses in structure also arise; thus, for example, the system of sixty corpuscles has its internal parts arranged similarly to the system of forty, in fact, it has the same arrangement as the system of forty with an additional ring of twenty corpuscles placed round it. In the same way, the system of forty corpuscles corresponds with the system of twenty-four, with an external ring of sixteen, while twenty-four arrange themselves in the manner of eleven with an additional ring. Such similarities of arrangement will give to the system in which they occur similarities of periods of vibration, and explain the homologous series of lines which are found in the spectra of elements lying in the same group of Mendeleeff's periodic table.

In the table which follows all the arrangements of corpuscles are given with twenty in the outer ring. Fifty-nine is the smallest number of corpuscles which place themselves with an outer ring of twenty, while, with numbers greater than

sixty-seven, the outer ring will contain more than twenty corpuscles.

| | I. | II. | III. | IV. | V. | VI. | VII. | VIII. | IX. |
|---|---|---|---|---|---|---|---|---|---|
| Total number of corpuscles. | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 |
| Number of corpuscles in successive rings. | 2<br>8<br>13<br>16<br>20 | 3<br>8<br>13<br>16<br>20 | 3<br>9<br>13<br>16<br>20 | 3<br>9<br>13<br>17<br>20 | 3<br>10<br>13<br>17<br>20 | 4<br>10<br>13<br>17<br>20 | 4<br>10<br>14<br>17<br>20 | 5<br>10<br>14<br>17<br>20 | 5<br>10<br>15<br>17<br>20 |

The stability of the outer ring is small when the number of corpuscles within it is small, and, in the example given, if the number in the inner rings falls below thirty-nine, the outer ring will collapse, and a new arrangement appear, with an outer ring of nineteen instead of twenty. With fifty-nine corpuscles, although the outer ring is unstable, no corpuscle can be detached permanently, for a break up of the arrangement would follow.

Passing, however, to the next member of the table, the atom-model containing sixty corpuscles, the stability of the outer ring, although increased, is still small, and a corpuscle is easily detached. This process would carry away a negative unit of electricity, and leave the atom positively electrified. Only one corpuscle can be lost, for the subtraction

of more than one would reduce the total below fifty-nine, and the general arrangement would change.

In Chapter IV. it was shown that the phenomena of the electrolysis of liquids indicates a close connection between the electric charges of atoms and their chemical valency, and it seems probable that chemical combination is an effect of the inter-atomic electric forces. Thus the system of sixty corpuscles, as described above, will act as the model of a monovalent, strongly electro-positive atom.

From the system of sixty-one corpuscles, two may be detached; though, the stability of the outer ring being greater, with less facility. Here then we have a less electro-positive, divalent atom.

Similarly the arrangement of sixty-two corpuscles corresponds with a trivalent atom, with still less marked electro-positive properties.

At the other end of the series, the stability of the outer ring is very great, and, with the system containing sixty-six corpuscles, for example, it will be possible for a negative corpuscle to attach itself to the outside of the system with no change in general arrangement. The system, then, acts as an atom, monovalent, and strongly electro-positive. But a corpuscle added to the collection of sixty-seven will produce a change in the outer-

most ring, which must now contain twenty-one corpuscles and will be very unstable. The sixty-seven group then has no valency, in this resembling the elements at the other end of the row.

To the group of sixty-five corpuscles it is possible to add two beyond the normal number without general rearrangement: it represents a divalent electro-negative element. The system of sixty-four corpuscles corresponds with a trivalent electro-negative atom, and so on.

Now let us compare these theoretical results with the first two rows of chemical elements in Mendeleeff's periodic table, as set forth below:—

| I. | II. | III. | IV. | V. | | |
|---|---|---|---|---|---|---|
| Helium. | Lithium. | Beryllium. | Boron. | Carbon. | | |
| Neon. | Sodium. | Magnesium. | Aluminium. | Silicon. | | |
| | | VI. | VII. | VIII. | IX. | |
| | | Nitrogen. | Oxygen. | Fluorine. | Neon. | |
| | | Phosphorus. | Sulphur. | Chlorine. | Argon. | |

The first and the last element in each series have no chemical valency, while the valency of the others rises in order, so that we get monovalent, divalent, trivalent, and tetravalent atoms, as we pass from the ends of the rows. The elements at the left end are electro-positive, and those towards the right electro-negative.

The concordance of Thomson's theoretical scheme with the periodic properties of the

chemical elements themselves — a concordance almost Satanic in its exactness and verisimilitude —forces us irresistibly to believe that, in these hypothetical systems of revolving corpuscles we have models which reflect in some really intimate way the structure of the mysterious originals.

An outstanding difficulty of interpretation remains in the positive electrification required to keep the negative corpuscles in their orbits; and this difficulty waits for future elucidation.

At first sight we may well say that Thomson's corpuscle—one of the latest conceptions of science —does but carry us back to the ideas and speculations of Democritus, and justify the glorification of those ideas in the poem of Lucretius, though internal evidence seems to show that Lucretius himself did not find the explanation entirely convincing:—

> "Nec me animi fallit Graiorum obscura reperta
> Difficile inlustrare Latinis versibus esse."

If, however, in one aspect these modern corpuscles may resemble the hard, impenetrable atoms of the Greek philosopher and the Latin poet, such a resemblance vanishes when we identify them with the disembodied charges of electricity, mathematically studied by Larmor and Lorentz. If the corpuscle is a negative electron—a disem-

bodied ghost—an electric charge—we enter a region of knowledge the bare existence of which was unknown to the ancients.

The hard particle of Democritus, which, as late as the age of Newton, still served as a working hypothesis, gradually failed to respond to the demands made on its constitution by both philosophers and physicists, in their search for a conceptual model of the chemical atom. Pictures of mere lumps of stuff, similar in kind to the perception of matter-in-bulk given by our senses, were no help to the theories of the metaphysician, while the complexity of structure demanded by the facts of radiation as disclosed by the spectroscope, showed that an atom must be capable of many and various modes of vibration.

In extreme opposition to the hard impenetrable sphere of Democritus, we have Boscovich's idealistic conception of atoms as centres of force. This theory gave too little scope for definite development to serve permanently as a useful working hypothesis, and, in face of the phenomena of atomic radiation, it too seemed insufficient.

It seemed that a real advance had been made when Lord Kelvin applied the theory of vortex rings, developed by Von Helmholtz and himself, to explain the properties of the atoms of matter. A smoke ring, blown in air, soon dies away, but

even this evanescent thing, while it lasts, shows a definite separation from the surrounding medium, and maintains an independent existence. Air is an imperfect fluid, and movement in it is resisted by the frictional forces due to its viscosity, but, if we imagine the air replaced by a hypothetical perfect fluid, in which there is no viscosity, vortex rings, once formed, will persist for ever. In a fluid not quite perfect, their life will be long, though not eternal.

Here then was a striking representation of some of the most important properties of the chemical atoms. The structure of interlacing systems of vortex rings gave sufficient complexity to explain radiation, the infinite possibilities of variation in number and arrangement of the rings would account for the relations between different atoms as manifested in the periodic law, while the persistence of matter could be explained if a perfect or nearly perfect fluid existed as the basis of the vortex motion.

At this point we reach for the first time in our inquiry the idea of an all-pervading medium —an idea which has played such a large part in the development of physical science, that a considerable digression will be necessary. Newton explained the phenomena of light by a

corpuscular theory. He supposed that streams of corpuscles were projected from luminous objects, and produced the sensation of sight by impinging on the nerves of the eye. Newton's theory was ultimately abandoned, mainly for two reasons. The phenomena of refraction could only be explained by it on the assumption that the corpuscles travelled more quickly in dense media than in air, and this, always improbable, was eventually disproved. On the other hand, the theory failed to explain the phenomena of interference and diffraction of light, except by the addition of so many arbitrary supplementary hypotheses, that, in the end, it was borne down by the weight of its own superstructure.

This illustrates a case, oft recurring, not only in the realm of science, where men have been deceived and led to form opinions wide of the truth through the agency of certain resemblances to that truth. The corpuscular theory of light was put aside, but not before it had appreciably retarded the progress of science. The master-mind, the originator of the theory, had been withdrawn before altered circumstances and increased knowledge reversed the weight of evidence. He who would have been the first to detect the want of harmony, the first to move on to new conceptions in the search for truth, by the irony of fate, be-

came for a time, in virtue of his intellectual supremacy, a stumbling-block to his weaker brethren, and an impediment to the cause he had most at heart.

In recent years the discovery of radio-activity has revealed to us particles very like those that Newton used to explain ordinary light. The $\beta$ rays from radium are projected particles moving with velocities nearly approaching that of light itself. Newton's inscrutable insight, amounting almost to an instinctive knowledge of Nature, has again been demonstrated. His corpuscles cannot, indeed, explain the phenomena of ordinary light; but similar corpuscles we find do exist, and their properties as set forth by Newton are not so unlike those actually occurring in the working of Nature as men have assumed throughout the years which separate the establishment of the undulatory theory of light from the discovery of radio-activity.

The corpuscular theory of light was replaced by a theory of waves in a medium which already had been recognised by Newton as a necessary addition to his idea of corpuscles. Newton's difficulty, which caused him to reject the undulatory hypothesis, namely, the rectilinear propagation of light, and the consequent possibility of sharp shadows, was finally overcome by Fresnel and Young, who showed that shadows were the result of the minuteness of the wave-lengths of

light as compared with the dimensions of ordinary obstacles. This cleared the way for the wave theory as already formulated by Huygens, and there arose a definite physical need for the exact specification of an æther or luminiferous medium, pervading all space, and the interstices, if not the substance, of material objects. Such a medium, indeed, had long been imagined by philosophers, as a means of transmitting actions from one body to another, but its use as a physical explanation of the phenomena of light first indicated some of its necessary properties. The reflection of light from the surface of a glass plate, or its passage through certain doubly refracting crystals, such as tourmaline, modifies the light, which acquires properties not the same on all sides of the emergent beam. No wave system in which the direction of vibration is in the direction of propagation can show such differences, for the waves must be alike on all sides of their path, and it follows that the luminous vibrations must be transverse to the direction in which the rays are travelling. Transverse waves imply a certain amount of rigidity or elasticity of shape in the medium—such elasticity as is possessed by solids alone. No fluid when distorted has any tendency to return to its original form; it cannot transmit waves which depend on mere distortional displacements. Waves in a fluid

must be waves of compression and expansion, in which the direction of vibration is in the direction of propagation.

If, then, it is to carry a transverse wave-motion of an ordinary mechanical kind, the luminiferous æther must possess some of the properties of a solid, and one of the great problems of æthereal physics consists in formulating a medium possessing the necessary rigidity. Any elastic jelly theory leads to obvious difficulties when the passage of matter through the æther is considered, a passage which often proceeds with high velocity, but, as far as observation goes, is entirely unimpeded. Rays of light from the stars appear to reach the earth in straight lines, suffering no deflection on passing through the æther outside the atmosphere near the earth. This result suggests that the luminiferous medium is not disturbed by the movement through it of the earth with a velocity of eighteen miles a second—the speed with which the earth moves round the sun. On the other hand, the passage of light over the surface of the earth is not affected by a change in direction relative to the earth's total motion, the velocity of the light is the same whether it is passing with or against the motion of the earth. This result indicates at first sight a conclusion opposed to that formerly reached, namely, that the æther is at rest relatively to the

surface of the earth and is dragged along with the ground as it moves. It is possible to reconcile these results by certain suppositions as to the effect of moving matter on the absolute velocity of light within it, but the general dynamical problem of constructing a model of the æther on ordinary mechanical ideas of wave propagation has never been satisfactorily accomplished.

As long as the æther was invoked only to explain the phenomena of light, the difficulties of interpretation might well suggest doubts about the fundamental hypothesis as to its existence, but when Clerk Maxwell showed that it was possible to explain the phenomena of the electro-magnetic field by an æther having properties identical with those of the luminiferous medium, the evidence for both theories was strengthened almost indefinitely. Maxwell proved mathematically that the velocity of an electro-magnetic wave through free space determined the relative magnitudes of certain electric units, so that by comparing the values of the units the velocity could be calculated. Experiment showed that the velocity was the same as that of light; light became an electro-magnetic phenomenon, and optical science a branch of electricity. Many years afterwards, Maxwell's great work was confirmed by the direct experiments of Hertz, who detected the existence, and measured the speed,

of electro-magnetic waves, thus laying the foundations on which the practical art of wireless telegraphy is based.

If we accept the view that an atom is composed of a large number of corpuscles in orbital or oscillatory motion, the electro-magnetic radiation which constitutes light must take its rise from the accelerations of these corpuscles as they revolve in their orbits.

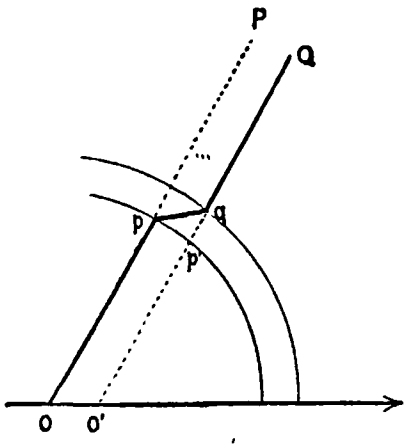


FIG. 35.

Faraday's conception of tubes of electric force, which we have used on page 169 to elucidate the theory of Röntgen rays, may here be revived in order to explain the radiation of ordinary light. As long as the charged corpuscle is moving forward with uniform velocity, it carries its attendant tubes with it in a steady manner, and no radiation occurs. When it is suddenly stopped, as we have seen, an electro-magnetic pulse spreads out from it, travelling with the velocity of light. Within

the sphere covered by this pulse, the tubes of force are rectified, so as to correspond with the new position of the corpuscle at rest, while outside it, in regions as yet unaffected by the change in velocity, the tubes are still moving forward with the original speed of the corpuscle. In the pulse itself, then, the electric tubes are bent more or less at right angles to the direction of propagation of the pulse, which spreads out from the corpuscle as centre. When tubes move, a magnetic force is produced at right angles both to their length and to their direction of motion; and thus, in the thickness of the pulse, a magnetic force exists, also at right angles to the direction of propagation of the pulse, that is, in the plane of the advancing wave-front, and, in that plane, at right angles to the direction of the electric force. The pulse is thus an electro-magnetic disturbance, and, as we have seen, is probably the physical interpretation of a Röntgen ray.

Now, if, instead of imagining the moving corpuscle suddenly brought to rest, we suppose that it is reversed in its path, and that this reversal occurs periodically, so that the corpuscle performs simple harmonic vibrations, we get, instead of a single thin pulse, a series of less abrupt but regularly recurring alternations propagated out from the corpuscle as centre. Each Faraday tube is

set into oscillation at its inner end, and transverse waves travel outwards along it, just as waves travel along a stretched cord, when one end is oscillated periodically by the hand. The distribution of electric and magnetic force in the advancing wave-front is exactly the same as in the case of the sudden pulse already studied: we get, in fact, a series of regular æthereal waves, in which there are electric and magnetic forces, both in the plane of the wave-front, and at right angles to each other in that plane. But such an arrangement is precisely that required to explain the phenomena of light.

In the simple case we have taken, the corpuscle oscillates backwards and forwards in a straight path: the vibrations travel as tremors along the tubes of force in one plane only; the resultant light is plane polarized. In the more general case, we must suppose that the corpuscle oscillates in a circular, or elliptical orbit, and the tubes of force will be displaced in corresponding motions; the tremors running along them will no longer be simple to and fro movements, but points on the tubes will describe curved paths. These paths continually change as the orbit of the corpuscle changes, and we get a complete model of the propagation of common, non-polarized light.

Faraday tubes, it is clear, give a very powerful

and convenient method of studying the phenomena of the electro-magnetic field, and indications are not wanting that they represent something more than a useful mathematical fiction. If the structure of the electric field is discontinuous in reality, as our tube-picture of it indicates; if the electric and magnetic effects of a charge of electricity are in reality exerted throughout the surrounding space by means of discrete tubes of force—vortex filaments in the æther, or whatever they may actually be—an advancing wave of light must be discontinuous also. If we could look at such a wave from the front, and magnify it millions of millions of times, we should see, not a uniform field of illumination, but a number of bright specks scattered over a dark ground. Each tube of force would convey its own tremors, and these would constitute light, but between them would lie undisturbed seas of æther.

Such an idea about the nature of a wave-front of light is very unexpected and surprising. We are inclined at once to relegate our tubes of force to a museum of conceptual curiosities. But it is a remarkable thing that certain evidence in favour of the discontinuous nature of a wave-front of light really does exist. It is impossible to examine the luminous effects with enough magnification to investigate the question, but, as we have seen,

ultra-violet light, and still more effectively Röntgen rays, are capable of ionizing a gas through which they pass. Here, it is the molecules of the gas which are affected, and, in examining the ionizing power of the rays, we are in effect using on them a microscope of molecular dimensions.

If the wave-front of a Röntgen pulse were continuous, all the molecules of the gas would be subject to the same disturbance. But, even with the strongest ionizing agency, nothing like one molecule in a million is found to be affected. Thus, if the wave-front be continuous, we must suppose that it is only those very few molecules which are in some peculiarly receptive state that are ionized. The stability of a molecule is greatly affected by temperature, and if a critical limit of stability were needed for a molecule to become ionized by the rays, we should expect that the ionizing power would rapidly increase with the temperature. Recently Mr. McClung has shown, however, that temperature has no appreciable effect. This curious result indicates that the ionizing action is independent of the state of stability of the molecule, and prevents us from finding in this way an explanation of the small number of the ionized molecules in the path of the rays.

It is possible that some other rare condition,

unaffected by temperature, may be the necessary preliminary to ionization by incident radiation; but it is also possible that the explanation of the smallness of the ionization is to be sought in the idea that the advancing wave is discontinuous, and is composed of a number of parallel tremors running along discrete tubes of force. The tubes of force being scattered at wide intervals through the æther, comparatively few molecules would lie in their paths, and only a few would be affected by waves running along the tubes. Matter has been analysed into discrete particles; electricity has been shown to be made up of indivisible units; and now it seems probable that light in physical reality, as well as in text-books of optics, is composed of a number of separate rays.

From the time of Maxwell onwards electro-magnetic considerations have formed an essential part of any theory of the æther. It is certain that luminous and electro-magnetic radiations are essentially the same in kind, and only differ in the length of the waves. These waves are very much longer when produced by ordinary electro-magnetic apparatus than when waves of light are emitted by the electro-magnetic processes of atomic vibration. We may, of course, cease to try to represent the properties of the

æther by means of any imaginary mechanical model, and, regarding light as a system of electro-magnetic waves, push the inquiry no further. Such a mode of formulation might be satisfactory if we restricted ourselves to the phenomena already mentioned, but at least two considerations prevent our resting content with a mere series of electro-magnetic equations as a final explanation. While radiation-effects of all kinds may be successfully co-ordinated, no conception is thus given of the nature of a static electric charge, or of an ordinary electric current, and there seems, on this mode of representation, no means of attacking the problem of the nature of gravitation, which must some day be explained in terms of the universal medium, if that medium is to survive as a permanent conception in physical science.

Attempts are, therefore, still being made to describe ideal models which shall represent the properties of the æther by familiar mechanical conceptions. If such a model is successfully constructed, it will not necessarily represent the actual structure of the æther; that is not its object. The primary function of such a successful model is to justify our theory of the æther as expressed in Maxwell's electro-magnetic equations, in the other equations requisite to

explain electric charges and currents, and, if possible, to suggest an explanation of gravitation also.

Nowadays, the tendency is to give up the old elastic solid view of the æther, and to secure the necessary rigidity in another way. A top when spinning possesses rigidity of position. It maintains its vertical position against the effects of its weight, and any displacement from the vertical is followed by definite oscillations around the mean position. These phenomena can best be studied in the gyroscope, which has now found a practical application in the Whitehead torpedo, where a direct course is kept by the tendency of a spinning wheel to maintain its axis of rotation undeviated. On these principles, Lord Kelvin has described a gyrostatic æther, in which the rigidity is secured by the motion of some still more primitive material.

Following the line of thought indicated by Lord Kelvin with his conception of the vortex atom, we now conceive matter to be an æthereal manifestation. But the simple vortex ring itself has failed to meet the demands made upon it. "The fluid vortex atom," says Larmor, "faithfully represents in many ways the permanence and mobility of

the sub-atoms of matter; but it entirely fails to include an electric charge as part of their constitution. According to any æther theory, static electric attraction must be conveyed by elastic action across the æther, and an electric field must be a field of strain, which implies elastic quality in the æther instead of complete fluidity: the sub-atom with its attendant electric charge must therefore be in whole or in part a nucleus of intrinsic strain in the æther, a place at which the continuity of the medium has been broken and cemented together again (to use a crude but effective image) without accurately fitting the parts, so that there is a residual strain all round the place."

It will be noted that any such theory, by which matter, the subject of experimental mechanics, is explained as an æthereal manifestation, changes the point of view from which we regard mechanical models of the æther itself. Æther, being now regarded as a sub-material medium, is not necessarily described by the experimental laws with which the facts of ordinary mechanics conform. In dealing with the æther, we are on an entirely different plane, and have no right to assume that a mechanical model of its properties is possible. However, as our

dynamical science is based on the phenomena of matter, we continue to describe the æther in terms of semi-mechanical models, though, strictly speaking, the mere statement in mechanical terms of the problems involved may be in itself misleading. Nevertheless, the success which is attending recent æthereal theories of material phenomena seems to indicate that the æther has in truth properties not unlike those of the material substances with which we are acquainted.

We are now in a position to gather together the various threads, philosophical, mathematical, and experimental, we have been following in this and the preceding chapters. The corpuscle of J. J. Thomson, the electron of Stoney, Larmor, and Lorentz, is represented in the æthereal world by Larmor's conception of a centre of intrinsic strain. Unlike the vortex atom, this strain-centre is not a part of the medium for ever separated from the rest; the strain alone persists, the part of the æther which is affected by it constantly changes as the sub-atom is moved. The æther is stagnant, and the sturdy ghosts which constitute matter float to and fro through it as waves pass over the surface of the sea. Such a persistence in time with mobility of space

would be impossible for a strain-form in any elastic solid æther, but can be secured by a rotational æther of the type described by Lord Kelvin.

According to this view, then, an electron or unit charge of electricity is a centre of intrinsic strain, probably of a gyrostatic type, in an æther, which is also the medium in which are propagated the waves of light and wireless telegraphy. Moreover, the electron is identical with the sub-atom which is common to all the different chemical elements, and forms the universal basis of matter. Matter, at any rate in its relation to other matter at a distance, is an electrical manifestation; and electricity is a state of intrinsic strain in a universal medium. It is prior to matter, and therefore not expressible in terms of matter; it is sub-natural if not super-natural.

Thus, from the side of æthereal physics, is reached the conception of an electron theory of matter. Within the last few years experimental confirmations of the fundamental conceptions of that theory have given it a firmer position than could be hoped at the time the theory was formulated.

The property of mass, the most fundamental

property of matter for dynamical science, is explained by the electron theory as an effect of electricity in motion. Forasmuch as a moving charge carries its lines of electric force with it, it possesses something analogous to inertia in virtue of its motion. The quantitative value of this effect has been calculated by Thomson, Heaviside, and Searle. Definite experimental evidence has been given by Kaufmann, who finds that the ratio $e/m$ of the charge to the mass for the corpuscles ejected by radium diminishes as their velocity increases. The charge is almost certainly constant, and thus the mass must increase with the velocity. Theory shows that, for a slowly moving corpuscle, the electric inertia outside a small sphere of radius $a$, surrounding the electrified particle, does not depend on the velocity, and is measured by $2e^2/3a$ where $e$ is the electric charge on the particle. But when the velocity of light is approached, this electric mass grows very rapidly; and, on the assumption that the whole of the mass is electrical, Thomson has calculated the ratio of the mass of a corpuscle moving with different speeds to the mass of a slowly moving corpuscle, and compared these values with the results of Kaufmann's experiments.

| Velocity of Corpuscle in Centimetres per Second. | Ratio of Mass to the Mass of a slowly moving Corpuscle. | |
|---|---|---|
| | Calculated. | Observed. |
| $2.36 \times 10^{10}$ | 1.65 | 1.5 |
| $2.48 \times 10^{10}$ | 1.83 | 1.66 |
| $2.59 \times 10^{10}$ | 2.04 | 2.0 |
| $2.72 \times 10^{10}$ | 2.43 | 2.42 |
| $2.85 \times 10^{10}$ | 3.09 | 3.1 |

In this remarkable manner has it been possible to obtain experimental confirmation of the theory that mass is an electrical phenomenon.

To explain all the properties with which we know the chemical atoms to be endowed, and more especially their power of complex radiation, it is necessary to represent an atom as a structure containing a large number of electrons in steady orbital motion round each other, somewhat as the planets move within the solar system. The attraction of gravity is independent of the position of a body, and is unaffected by any kind of screen. It would be difficult to explain such results if the electrons, on which gravity acts, were crowded together ; thus it seems necessary to suppose that the electrons occupy an exceedingly small fraction of the whole volume of the atom, just as the planets occupy a very small fraction of the space comprised within their orbits.

The mass of the electron being electrical in its nature, we may calculate the size of the individual electrons or corpuscles from the expression $2e^2/3a$ for the electrical mass. We know the values of $e$ and of $e/m$, and from these results we calculate $a$ to be about $10^{-13}$ centimetre. According to Thomson, $a$ is the radius of a sphere outside which the momentum of the electric field exists. It seems reasonable to identify this sphere with the effective dimensions of the electron itself.

We have already seen that, in a substance like water, where the molecules are fairly closely packed, one cubic centimetre contains about $3 \times 10^{22}$ molecules, or, let us say, $10^{23}$ atoms. Along each edge of the centimetre cube about $4 \times 10^7$ atoms are ranged, and thus we may take the effective radius of an atom to be about $5 \times 10^{-8}$ of a centimetre. Its volume would be about $10^{-23}$ of a cubic centimetre, while the volume of an electron, according to the above estimate of the radius, is about $4 \times 10^{39}$. Thus, while the diameter of an electron is less than the hundred-thousandth part of that of an atom, the volume of an electron is only about the $10^{-16}$ part of that of an atom, and their relative sizes have been compared by the illustration of a mouse roaming about inside a cathedral.

On the planetary theory of the atom, the moving

electric charges produce a magnetic field, just as does a current flowing round the coils of a galvanometer. Thus, conversely, an impressed magnetic force should modify the movement of the electrons, and affect their radiation, which depends on the rate of acceleration of their motion. The theory of this effect was considered by Lorentz and Larmor, who predicted the subdivision of the spectral lines, afterwards experimentally discovered by Zeeman.

The connection of the electron theory with the phenomena of radio-activity has already been considered. The conception of an atom as a system of electrons in rapid orbital motion naturally suggests its occasional disintegration; the possibility of such disintegration had been treated as a difficulty of the theory by Larmor before the discovery of radio-activity directly indicated its occurrence. Some attempts have recently been made to trace the *modus operandi* of atomic disintegration.

If an atom consists of a system of electrons in orbital movement, the acceleration of their motion must involve a constant radiation of energy. A single negative electron, revolving round a positive centre of greater mass, would radiate its energy very rapidly. Two electrons, at opposite ends of a diameter, would radiate much more slowly, and, as the number of electrons increases, the

rate of radiation quickly diminishes. A structure like an atom, with its mass-acceleration balanced, would maintain its energy with very little loss for long periods of time, measured, perhaps, in millions of years. Still, loss of energy does occur, and it remains to consider its cumulative effects. The problem for one or a small number of electrons is similar to that given by a body moving in a circular orbit, retarded by a frictional resistance, a problem familiar to ordinary dynamics. The revolving body tends to drift towards the centre of its orbit, and thereby the attraction towards that centre will clearly increase its velocity, and the planetary body moves faster and faster in constantly decreasing orbits, and might finally topple over into a new configuration. If the velocity of light were approached, the mass, as we have seen, would increase, and it has been argued by Lodge that this sudden increase in mass will not be compensated within the system, and will involve a sudden gain in momentum which may result in an explosive disintegration of the atomic system, such as occurs in the phenomena of radio-activity. It seems likely, however, that, when the increase in mass began to occur, it would tend to check the increase in velocity which produced it, and thus fortunately act towards stability. Such a

transition must be rapid; there is no resting-place between one atomic configuration and another.

Another account of possible disintegration has been suggested by J. J. Thomson. In the complex system of many thousand corpuscles, constituting an atom of a heavy chemical element, inter-corpuscular forces, as well as those acting towards the centre of the system, must be considered. It is probable that such forces would counteract any tendency on the part of the electrons to fall without limit towards the centre, and in so doing to acquire very high velocities as their energy was lost by radiation. In these circumstances the effect of radiation is to diminish the velocity of rotation. The rate of loss of energy, as we said above, is very slow; in a continuous ring of corpuscles it would vanish, but still, except in special circumstances, with a number of separate corpuscles a slow loss is always going on. Now it is easy to conceive a system of revolving electrons, stable while moving fast, which becomes unstable when the velocity of rotation sinks to a critical value. For instance, as we have already done above, let us represent the structure of an atom by a number of little magnets thrust through corks, floating on the surface of water with their south poles vertically

upwards. Let the north pole of a large bar magnet be placed above the water. It will attract the south poles of the little floating magnets, which repel each other, and thus draw them together till the repulsive forces balance the attractive ones. To take a very simple case, suppose that we had six little floating magnets, and that we gave the water and the magnets floating on it a circular movement so that the six little magnets revolved round the centre. If the movement were fast enough, the six magnets would place themselves all on the circumference of a circle at equal distances from each other ; and this arrangement is permanent as long as the velocity of rotation remains above a certain value. Presently, however, the velocity diminishes to such an extent that the configuration becomes unstable, and a sudden rearrangement occurs. The magnets place themselves five on the circumference of the circle, and one at the centre, in the positions they assume when the whole system is at rest. Such a model may be crude, but it is strikingly effective. As we have seen above, Thomson has correlated it with the system of corpuscles revolving within a sphere of uniform positive electrification, and, in this case also, has shown that similar changes of configuration must follow a diminution of velocity. In the complex system constituting an atom, it is

easy to imagine that such a sudden change in the conditions of stability might well result in an explosive rearrangement, in which the atom might be shivered to pieces, and give rise to the phenomena of radio-activity.

A more fundamental suggestion has been made by J. H. Jeans, who imagines that radio-activity may result from the coalescence of positive and negative electrons. On this idea the energy of radio-active atoms is supplied by the actual destruction of matter.

J. J. Thomson has also described a process of continual evolution and disintegration of matter. The primordial chaos is filled with corpuscles, in positive and negative pairs, scattered throughout space. By mutual forces, due to the accompanying strains in the æther, they attract each other, and produce mutual accelerations. Two doublets meeting with very high velocities will probably part again after a merely hyperbolic acquaintance, but the mutual accelerations imply loss of energy by radiation, and thus the average velocity will be reduced till occasionally permanent connections between corpuscular doublets may be formed. Gradually these systems grow in size and complexity, and the chemical atoms are evolved, many of their periodic relations being represented in a wonderful manner by the crude model of systems of floating magnets

already described. But none of these atoms are dead; they all possess corpuscular motion, and, as radiation produces loss of energy, occasional positions of instability are reached at which re-arrangement is necessary. Such positions will occur more frequently in complicated structures, and thus it is natural that radio-activity is more marked in the heavier atoms.

Darwin and Wallace revealed to us the evolution of living organisms; it seems possible that Thomson, Larmor, and Rutherford may enable us to trace the corresponding process in inorganic matter.

One of the most remarkable of the purely mechanical models of the æther has been described recently by Professor Osborne Reynolds in his treatise entitled, "The Sub-Mechanics of the Universe." In this scheme the æthereal-strain theory of matter has been formulated in a definite mechanical manner, and mobility for the strain-form secured by other than gyrostatic conceptions of the medium. It is claimed that "there is one, and only one conceivable purely mechanical system capable of accounting for all the physical evidence, as we know it, of the universe. The system is neither more nor less than an arrangement, of indefinite extent, of uniform spherical grains

generally in normal piling so close that the grains cannot change their neighbours, although continually in relative motion with each other; the grains being of changeless shape and size." The grains are of minute size, small even compared with Thomson's corpuscles, their diameter being $5.534 \times 10^{-18}$ centimetre. The pressure in the medium is about 10,000 tons per square centimetre.

"In spaces in which there are local inequalities in the medium about local centres, owing to the absence or presence of a number of grains in deficiency or excess of the number necessary to render the piling normal, such local inequalities are permanent," they can move through the medium, though the grains do not move with them. The excess or deficiency passes along, as a wave passes over water. The form persists, though the substance does not move with it. Positive inequalities, if such exist, repel each other, and would thus pass away as far from each other as possible, but negative inequalities attract each other according to the laws of gravitation, and constitute the particles of matter. Matter, then, is constituted by regions of diminished mass, and this result led Reynolds to call his popular exposition of the theory "An Inver-

sion of Ideas regarding the Structure of the Universe."

Reynolds shows that these assumptions are consistent with the known numerical values of the gravitation constant and the velocity of light. Explanations are also given of numerous other physical phenomena, optical, electrical, &c.

The mathematical analysis by which these deductions are established is very complex and difficult, and it is yet too soon to say if this bold attempt will stand the criticisms that will be directed towards it; but Professor Osborne Reynolds' great reputation, and the twenty years he has laboured at this research, will ensure for it a careful consideration from those competent to judge of its merits.

Should this, or any similar theory, stand the test of time, a mechanical specification of the universe will, in one sense, have been obtained. But it is evident that the success of such theories does but shift the mystery of the unknown. Matter is a persistent strain-form flitting through a universal sea of æther: we have explained matter in terms of æther. Æther in its turn is described as a fairly close-packed conglomerate of minute grains in continual oscillation: we have

explained the properties of the æther. So be it. But what of the grains of which the æther is composed? Are they "strong in solid singleness," like the one-time atoms of Lucretius? Or have they parts, within which opens a new field of complexity? Of what substance are they made? Has a new æther more subtle than the first to be invoked to explain their properties, and a third æther to explain the second? The mind refuses to rest content at any step in the process. An ultimate explanation of the simplest fact remains, apparently for ever, unattainable.

# CHAPTER VIII

## ASTRO-PHYSICS

"For who so list into the heavens looke,
And search the courses of the rowling spheares,
Shall find that from the point where first they tooke
Their setting forth, in these few thousand yeares
They all are wandred much; that plaine appeares:
. . . . . .
Ne is that same great glorious lampe of light,
That doth enlumine all these lesser fyres,
In better case, ne keepes his course more right,
But is miscaried with the other Spheres:
For since the terme of fourteene hundred yeres,
That learned Ptolomæ his hight did take,
He is declyned from that marke of theirs
Nigh thirtie minutes to the Southern lake;
That makes me feare in time he will us quite forsake."

—SPENSER, *The Faerie Queene*, Book V.

THE origins of the ancient science of astronomy are lost in the mists of the past. Unlike some of the subjects we have discussed in this volume, its phenomena are familiar to the most unobservant of mankind, and some of these phenomena, in the apparently unfailing regularity of their manifestation, have served as measurers of time and forewarners of seasons during immemorial ages.

The recognition of the possibility of slow change in this regularity, and the attempt to detect such change by careful observation, are also an old story, while unusual manifestations, such as comets and eclipses, were, till comparatively recent times, regarded with fear and consternation, and considered as direct signs of Divine wrath.

Yet the oldest of the sciences is also, in some respects, if not the newest, at any rate among the youngest of the fraternity; for in its recent growth, its spirit of adventure, its capacity of immediate development, it shows all the characteristics of sturdy youth.

In the history of the different branches of physical science, it is constantly found that periods of great activity and advancing knowledge alternate with periods when, owing to the exhaustion of the possibilities of the apparatus available or of the methods of research employed, progress seems almost to cease.

Fifty years ago astronomy appeared to be sinking into one of these periods of comparative stagnation. The power of the telescope seemed almost to have reached a limit, for although improved and larger instruments were continually being produced, the revelations they made were apparently unworthy of the knowledge and skill lavished on their manufacture. It was

not more elaborate instruments, but new methods of research that were wanting.

But even while the older astronomy was flagging, the new method had appeared, and was only waiting for development in its apparatus to carry forward the torch of learning into untrodden paths, and even to rival the results of Adams and Leverrier, who had stirred so profoundly the imagination of their generation.

The new science of astro-physics dates from the application of the spectroscope to astronomical problems. The spectroscope itself illustrates the progressive triumph of modern science, for it is the work neither of one man nor of one century. Its principles have been gradually developed and its construction elaborated throughout a couple of hundred years. Newton was the first to analyse the light of the sun by a prism, to study the spectrum thus obtained, and to show that it consists of rays of every colour, which, when blended together in the eye, produce the sensation of white light. In the year 1802, Wollaston noticed that the spectrum of the sun's light was crossed by a number of fine dark lines, and the relative positions of these lines were shortly afterwards carefully mapped by Fraunhofer, whose name the lines have borne since that time.

The next great advance was made by the chemists Bunsen and Kirchoff, who repeated and amplified, in the year 1860, an almost forgotten experiment of Foucault, though the principles which underlie their discovery had previously been understood by Sir George Stokes. Any vibrating system—a child's swing, for example—is set into violent oscillation if impulses are given to it exactly timed to coincide with its own proper period of vibration. Just as the particular piano wires which are tuned to a particular note will be set in vibration when that note is sounded in their neighbourhood, so the molecules or atoms of a gas will be set in vibration by waves of light which possess a period of oscillation corresponding to their own. A complex wave of light, then, passing through a collection of such molecules or atoms, will have those constituent waves absorbed which are tuned to the characteristic periods of the absorbing systems. Substances, that is to say, absorb the particular kinds of radiation which they would themselves emit when hot.

Applying these principles to the Fraunhofer lines, Stokes held that when coincidences existed between their positions and those of the bright lines obtained by examining with a prism the light of incandescent vapours, the coincidence

was to be interpreted by the supposition that similar vapours were present in the atmosphere of the sun, and absorbed the light coming from the hotter regions below them.

In 1860 Bunsen and Kirchoff, without knowing that Foucault had anticipated them in 1849, devised and carried out an experiment on the artificial production of Fraunhofer lines. They passed the light of an electric arc, which gave a perfectly continuous spectrum with no such lines as those in the solar light, through the vapour of sodium volatilised in the comparatively cool region of a spirit lamp flame. They had the joy of seeing a black absorption line, coincident with the bright line given by hot sodium vapour, crossing the continuous spectrum of the arc, just as the black line, called by Fraunhofer the line *D*, crosses the spectrum of the sun. The possibility of determining the chemical constitution of the heavenly bodies had opened before the eyes of man.

Hitherto the sun had been studied chiefly in relation to the earth and the general solar system, while little else was known about the stars than their apparent relative positions on a hypothetical celestial sphere. Their composition and physical condition were held to be outside the range of any definite scientific investigation; subjects, per-

haps, better fitted to the romancer than to the serious student. But with the advent of the spectroscope, sun and stars, in a new aspect, re-entered the realm of exact knowledge, and began to give up the secrets of their composition and state.

Many of the chemical elements known on the earth were detected in the sun, while Fraunhofer lines, not corresponding to the spectrum of any terrestrial substance, suggested the existence of solar elements hitherto unrecognised. The spectra of the stars were found to vary, some showing the presence of hydrogen only, while others indicated the existence of constitutions more nearly approaching that of our sun.

The structure of the nebulæ, those vast, vague sources of luminosity, had long been a matter of speculation. Were they clusters of innumerable stars, so minute and so distant that the most powerful telescopes could not resolve them, or were they, indeed, as their name indicated, foregatherings of cloud-like, light-giving vapours? The question was settled as soon as the spectroscope was turned towards their light. A continuous gradation in properties was found between stars and nebulæ. Most nebulæ gave continuous spectra, indicating high density and pressure at

the source of radiation, but some few gave bright lines on a dark background—the spectra, not of dense suns surrounded by cooler atmospheres, but of masses of -glowing vapour of great tenuity—the beginnings, perhaps, of suns and worlds yet to be.

Then came a pause in the progress of this new branch of knowledge. The spectroscope alone seemed to have told all it could to the human eye. A more sensitive instrument was needed to receive its messages, to intensify them, and to interpret them to the senses of mankind. It was not till photography was employed to record the results of spectrum analysis that the full power of the spectroscope was understood. Although previous attempts had been made by means of inferior processes to photograph the spectra of the sun and stars, the great success of the method dates from the application of the dry gelatine process by Sir William Huggins in 1876

The photographic method has many advantages over direct visual observation. The sensitive plate can be exposed for a considerable length of time, and the effect of the light on it is cumulative. Excessively feeble light will, by prolonged action, produce a sensible impression on the photographic plate when it would be quite

insensible to the eye, which has none of this power of gradually storing and intensifying its impressions. Again, the photograph will record ultra-violet radiation to which the nerves of the eye do not respond, and, in this way, it has revealed many invisible lines. Finally, the photograph forms a permanent record, to which reference can be made at any future time, and permits measurements, more accurate than those made by direct visual observation, to be obtained at leisure in the laboratory many hours or days after the exposure. In several observatories, systematic records are kept of the state of the sky from night to night, and, more than once, when a new star has been detected, its previous history has been unfolded by reference to photographic plates exposed before the existence of the new star was suspected.

Two methods of obtaining spectra are known to the physicist, the instruments used being respectively the prism and the grating. The grating consist of a number of equidistant parallel scratches ruled on a reflecting surface of polished metal or on a transparent surface of glass. The scratches are very close together, many thousands of them being included in the space of an inch. When a wave of light falls on a metallic grating, the scratches refuse to reflect

the light. The distances between the scratches are comparable with the minute wave-lengths of light, and thus different waves are differently treated by the grating. The component rays of a complex beam of light are separated from each other, and, if the source of light be a narrow slit, a number of parallel images are formed, and a spectrum is obtained. The deviation of any particular wave, such as the yellow sodium ray, will obviously depend on the wave-length of the light, and, for the same grating, will depend on this wave-length alone. The spectral lines obtained will therefore have positions simply depending on the wave-length or period of vibration of the corresponding rays of light; in this differing from the similar lines given by the prism, which depend in position on the qualities of the glass as well as on the periodic times of vibration of the different rays.

The sharpness of definition of a spectrum taken from a grating depends on the accuracy with which the scratches are ruled, and thus the perfection of the grating depends on our power of moving the scratching tool through exactly equal intervals between two scratches. To control the movement a perfect screw is required, and to Professor Rowland's improvement in the manufacture of screws in 1882, and to his idea of using them to rule gratings on concave metallic surfaces, is directly

due the possibility of making adequate use of the resources of photography in the province of solar and stellar spectrum analysis. The arts and the sciences are closely related; an advance in one of them often leads to a corresponding advance in the other, and it is not always science that leads the way.

The concave grating banished the need for a lens to focus the rays after diffraction, and an image of the spectrum could now be obtained from the grating alone. Glass is opaque to much of the ultra-violet radiation, in which sunlight, at any rate, is very rich. Prismatic spectra and spectra taken with plane gratings and lenses do not show the ultra-violet lines. But, by the use of a concave grating and a reflecting telescope, the presence of glass becomes unnecessary, and investigation can be prolonged into the ultra-violet region till the increasing absorption of the earth's atmosphere prevents the rays from reaching the surface of the ground.

Glass is opaque to the infra-red radiation also, and here again the advantages of the concave grating are manifest. The infra-red spectrum has been examined, chiefly by Professor S. P. Langley of Washington, through the heating effects of its constituent rays. Professor Langley uses an instrument called the bolometer, in which the heating

effects of different parts of the spectrum, and consequently the position of the dark lines, are determined by measuring the change in electric resistance of a very thin strip of platinum exposed to the radiation. This form of platinum thermometer is extremely sensitive, and the spectrum of the sun has been mapped far below the limits within which the eye responds to the stimulus of light.

Perhaps the most striking and interesting results given by the combination of camera and spectroscope are those obtained by the determination of the change in the refrangibility of light produced by relative motion of approach or retrocession of the source of light and the receiving station. Let us imagine that waves are proceeding from some source which remains at rest. A certain number of waves reach an observer in one second. If, however, the observer is approaching the source, it is evident that, as he is going to meet the waves, a greater number of them will reach him in one second than when he was at rest. Similarly, if the observer move away from the source, the number of waves which reach him in a given time will be less than before. The same effects will be produced if the observer be stationary and the source of light move. Doppler's principle, as this change in periodic time is called, is well illus-

trated in the case of sound. Here the frequency of wave impulse on the ear determines the pitch of the note heard, and it is easy to detect a distinct flattening by a semitone or more, as the whistling engine of an express train passes the observer. The source of the waves of sound still vibrates with the same frequency, the change is only in the number of impulses reaching the observer per second.

The frequency with which waves of light are received by the optic nerve determines the colour perceived by the brain, and also the amount of refraction in passing through a prism. Thus the colour of a ray of a single definite wave-length, as well as its position in the prismatic spectrum, will be different from the normal value when the source of light and the observer are moving relatively to each other. An approach will result in a shifting towards the blue end of the spectrum owing to the increase in frequency; a recession will involve a reddening of the light, or a movement of the spectral lines towards the red end of the spectrum. Owing to the great velocity of light, the change will relatively be much less than in the case of sound. Light travels about 186,000 miles in one second, and, great though the speeds of the stars may be, they fall far short of such tremendous values. A velocity of eighteen miles a

second, for example, the velocity of the earth in her orbit, is but the ten-thousandth part of the velocity of light. This velocity of approach, then, would involve a change of the ten-thousandth part in the period of vibration of the incident light. The whole visible spectrum, from the red to the violet of the rainbow, includes a range of frequencies of about an octave, that is, the period of vibration of the extreme red is about double that of the extreme violet. A velocity equal to that of the earth, then, would involve a change in position of a spectral line of about the five-thousandth part of the total length of the spectrum. Many stars are approaching or receding from the earth at velocities higher than that which we have taken as an example, but still the changes in position to be measured are very small, and refined methods and great experimental skill are needed for accurate results.

The problem of determining the movement of a star travelling along the straight line joining it to the observer would, before this principle was discovered, have seemed one of the most hopeless problems which a cynical scientific sceptic could propose for solution to the physicist. Yet such problems are now solved daily, or rather nightly; solved, indeed, much more readily than they could

be if the star were moving across the line of sight. In the latter case, even if a knowledge of the distance makes the determination possible, prolonged observations are needed, extending over months or years, till the movement becomes apparent at the distance of the earth. Many stars are so distant that no such cross movement could be detected in any reasonable time. If, however, the star is moving towards or away from the earth, the spectroscope is turned towards it, and in the short time required to fix a photographic impression, develop and print the plate and measure the lines upon it, the velocity of the star can be determined.

Another application of the same principle has enabled us to demonstrate directly the rotation of the sun on its axis, and to separate those absorption lines in the spectrum of the sun's light which are due to the effect of the earth's atmosphere from the lines of true solar origin. One limb of the sun is, at any moment, approaching the earth, while the opposite limb is in like manner receding. By pointing a spectroscope first at one limb and then at the other, a shift of the spectral lines is seen; and, from the amount of the displacement, the velocity of movement of the glowing gases which produce the lines of absorption can be calculated. Lines which are not shifted by

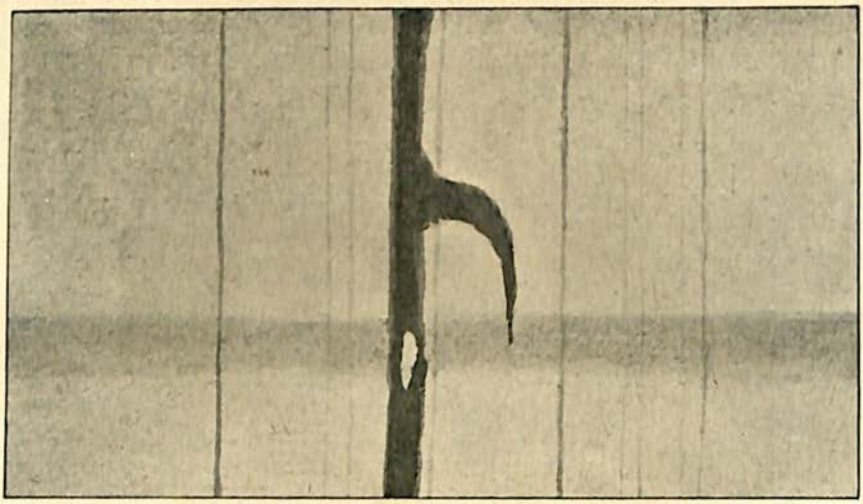


FIG. 36.—*C* LINE IN THE SPECTRUM OF A SUN-SPOT
(*Professor Hale*)

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this operation are clearly not of solar origin, and are consequently to be referred to absorption by the atmosphere of the earth.

Other problems in solar physics have been solved by the same method. The existence of sun spots has long been known; they were, indeed, familiar to the Chinese in very early times, and, in the middle of the nineteenth century, their periodic increase and decrease in a cycle of ten or eleven years was noted by western observers, and a coincident period of terrestrial magnetic phenomena was established. The structure and properties of sun spots were then seen to possess more than a local solar interest, and their importance with regard to terrestrial meteorology became manifest. It has long been held that sun spots were the seat of movements of gases on a gigantic scale in the solar atmosphere, and direct evidence of such storms is supplied by the spectroscope. Professor Hale gives a drawing of the spectrum of a sun spot in the neighbourhood of the *C* line. This drawing is reproduced in Fig. 36. The slit of the spectroscope was directed to the sun's disc so as to include the area covered by the spot. The figure shows a small part of the spectrum, which extends from left to right across the paper. The faint horizontal dark line shows the effect of the sun

spot, from which much less light proceeds than from the rest of the sun's surface. Several faint Fraunhofer lines cross the diagram vertically, and it will be seen that these lines are still dark lines in the sun spot region. The sun spot itself, then, must be the source of continuous radiation, from which definite rays are abstracted by cooler gases in higher regions, the process being identical with that going on in other parts of the sun. The heavy dark line crossing the figure from top to bottom is the *C* line to which reference has been made. It is much stronger and darker than any of the other lines shown. In the neighbourhood of the sun spot, like the fainter lines, it still shows dark, but in its centre is a bright patch or reversal of the line. This intense luminosity indicates that, superposed on the layer of gas which absorbs the light, is a mass so hot that its radiation is even greater than the normal radiation from the sun's surface. The curious hook-like appendage to the line, which begins as a fine point in the middle of the sun spot absorption, and ends above by fusing with the *C* line, tells of an extraordinary outrush of cool hydrogen coming from the centre of the sun spot area, and travelling outwards with a radial velocity of about one hundred and twenty miles a second. In its outward course it passes away from the sun spot area, and finally comes to

rest at a distance of thirty to forty thousand miles from its point of origin. Its absorption then of course coincides in spectral position with the normal *C* line.

Similar work, carried on in several observatories, has thrown much light on the movements of the prominences, which come into view at the edge of the sun's disc, and seem to be connected intimately with the spots. These enormous masses of glowing gases produce bright line spectra, and the displacement of the lines gives the movement in one plane, while direct visual observation gives that in a plane at right angles to the first. Thus the motion of the prominences can be completely specified. Their velocities are often as high as 200 or 300 miles a second.

It seems unlikely that such high velocities can be the result of differences of gaseous pressure and the convection currents thus engendered. They are more probably to be explained by the local action of some explosive source of energy, by which matter is projected with great violence.

The application of Doppler's principle to stellar movement has led to other results quite as remarkable as those already described. Our sun is a single system, but many of his fellows among the stars are accompanied by partners; the two

existing in more or less close conjunction, and showing all the signs of a common origin. Some of these double stars can be examined by telescopic means, but the majority of them lie too close together to be thus separated. Often, too, one of the pair is not luminous, and therefore would never be visible. In this class are probably to be placed variable stars, such as the star known as Algol or $\beta$ Persei, the light from which undergoes periodical fluctuations in intensity. The light keeps constant for the greater part of the cycle, and then diminishes for a short time before again rising to its normal value. This behaviour was long suspected to be due to the partial concealment of the star by a dark companion or satellite, and the surmise was confirmed by the spectroscope, which shows that the star is always receding from us before the loss of light and approaching after it. This result is exactly what we should expect on the eclipse theory, the dark companion being so nearly of the same size as the visible Algol that the joint motion is similar to that of two partners waltzing round each other rather than like the revolution of a small satellite round a large central body, which remains nearly stationary. In other cases, such as that of $\beta$ Lyræ, the intensity of the light is never constant, but undergoes continual

variation, accompanied by complicated changes in the spectrum. A partial explanation is probably to be sought by imagining two luminous bodies, which revolve round each other, and send to the earth more light when they lie side by side than when one lies behind the other and to a certain extent obscures it.

It is evident that the double nature of such systems can be demonstrated by variations in luminosity only in the few cases where the motion is in such a plane that one of the partners is periodically interposed between the other and the earth. Only about twenty Algol variables are, in fact, known. When this eclipse does not happen, the dark companion could never be detected without the aid of the spectroscope. By continuous records of the spectra of many stars, however, periodic changes in the lines have been observed, and the times of the orbital movements determined. Binary systems have been discovered with periods varying from a few hours to several years. In some cases the spectral changes merely consist in periodic shiftings of the lines. Here we probably have a luminous body and a dark companion revolving round their common centre of gravity. In other cases, a periodic doubling of the lines indicates two bodies, both luminous, but too near together and too far from us to be

separated by the telescope. The number of both classes seems to be considerable, and our visible universe must be studded pretty closely with dark stars, the existence of which is only to be detected in cases of their combination with some luminous companion.

Passing from these questions to the problems of our own planetary system, we find the same principle applied to the examination of Saturn's rings. These remarkable structures, which in the telescope look like rings of continuous matter encircling the planet, were long a puzzle to the astronomer. Theory indicates that such rotating rings of continuous matter, whether solid or liquid, would be unstable, and would break up under the forces which must necessarily exist. The alternative hypothesis, that the rings consist of a swarm of tiny meteorites, each revolving round the planet in its own separate orbit, was elaborated mathematically by Clerk Maxwell, but no confirmation of this view was obtained till Keeler examined the rings with the spectroscope. He found that the inner parts of the rings revolved faster than the outer parts, in accordance with the requirements of the meteoritic hypothesis. If, on the other hand, the ring were solid, the outermost parts would possess the highest velocity, on the same principle by which the circum-

ference of a fly-wheel moves faster than its inward parts.

While the knowledge of sun and stars delivered to us by spectrum analysis has been both extensive and striking, the interpretation of spectral phenomena has proved a much more complicated problem than was anticipated when Bunsen and Kirchoff's great discovery first placed the new method in the hands of investigators. The lines of the spectrum, whether bright or dark, were thought at first to be absolutely fixed and constant in position—that is, the modes of vibration of the atoms from which the light proceeded were imagined to be unaffected by any external circumstances. This supposed simplicity has been shown to be illusory. As we have seen, movement of the source and observer, although it may not alter the atomic vibrations, affects the number of them received in any time, and thus changes the refrangibility of the light they emit as it is received by the observer. But other variations, more fundamental in their origin, are known. Laboratory experiments have shown that the spectral lines alter their character with changes in the physical conditions of the experiments. It was thought that luminous gases evolved only bright, sharp lines. It is now found that

the lines may be broadened and softened by an increase in the pressure or the density of the gas, while, in some cases, a simultaneous shift in position may be produced. An intense magnetic field has been shown by Zeeman to result in separation of single lines into two or more components, in this fulfilling the predictions of the electro-magnetic theory of light, which suggests that some such connection is probable. The spectra of elements have long been known to depend on the temperature, the spectrum of the arc discharge often being different from that obtained by the use of a discontinuous spark, while neither correspond to the spectrum of the incandescent vapour existing in the flame of a gas-burner. More recent experiments have shown that traces of impurities may modify the spectrum considerably, while, in some cases, the presence of one substance will completely mask the spectrum of another.

The possibilities introduced by all these effects naturally complicate the interpretation of solar and stellar spectra. On the other hand, the very complications greatly increase the interest of the luminous messages, and the investigation of the connection between the external conditions and the nature of the spectra in the physical laboratory opens an almost limitless field to profitable re-

search. Co-operation between the laboratory and the observatory doubtless will elucidate gradually the fascinating problems of the nature of the celestial bodies.

The spectra of various substances differ widely in complexity. Some consist of a few lines, some of very many. Iron, for instance, emits light of at least two thousand different wave-lengths. Of recent years order has to some extent been introduced into our knowledge of complex spectra by the discovery that fairly simple relations hold between their wave-lengths or their frequencies of vibration. Simple formulæ have been devised, which in a general way express the connection between the frequency of one fundamental line and its companions, somewhat as can be expressed the connection between a musical note and its overtones. In many cases, however, it is impossible to bring all the lines of a spectrum into conformity with such a formula. Two or even three series of lines exist, and two or three formulæ are needed to co-ordinate their frequencies. That such distinctions possess a physical significance is shown by recent experiments of Lenard, who finds that the three series of sodium and lithium lines are separated in the flame of the electric arc, the outer shell of flame giving only the fundamental series,

while, in the physical conditions appertaining to the inner flame, the second and third series become dominant.

Some of the most interesting work now in progress relating to the sun is founded on Professor Hale's method of photographing the sun itself and its prominences by the light corresponding to one definite spectral line. Two of the commonest elements present in the sun are hydrogen and calcium, and these elements are marked by the strong lines H and K respectively. The resultant photographs, then, show the distribution of hydrogen or calcium throughout the region investigated. The spectra of the prominences at the edge of the sun's disc consist of bright lines, while some of the dark absorption lines of the light from the surface of the sun possess bright centres, like those shown in Fig. 36, indicating the existence of masses of luminous vapour lying above the reversing layer. These bright central lines give sufficient light for the purpose we are now considering, and the resulting photographs show the distribution of glowing clouds of vapour in the higher regions of the solar atmosphere. Even the dark absorption lines are only dark by comparison with the brighter background, and thus new photographs can be taken

with the darker sides of these reversed lines. The light then used comes from a deeper layer in the solar atmosphere, and as many as three calcium photographs have been taken in this way from a single line, showing the distribution of calcium at three different levels in the sun's envelope.

The method by which Professor Hale obtains these wonderful results consists in the employment of a spectro-helioscope possessing two slits. The solar light is focussed into an image by the telescope, passed through one of these slits, and thrown on a prism or grating. The spectrum thus produced shows the usual lines, and the second slit is fixed so as to coincide with the line by the light of which the sun is to be photographed. The light coming through the second slit is thus monochromatic light—simple light of the particular kind desired. The first slit is made to travel slowly over the disc of the sun, and the second slit, by appropriate movements, is kept constantly in position to allow the particular line to fall upon it. In this way a complete picture of the calcium or hydrogen flames above the surface of the sun can be obtained.

One of the striking features of recent photographs taken by this method consists in the well-marked differences in the distribution of hydrogen and calcium. The faculæ and prominences, which

stud the solar disc, contain floating clouds of hydrogen, and other clouds of calcium, but these clouds are often separate from each other, and possess distinctive forms which are well shown in Figs. 37 and 38, and can at once be recognised by an accustomed observer as due to hydrogen or calcium respectively. Prominent objects on the sun, such as spots, often show clearly only in one of these two kinds of light, when they are faintly seen or are quite invisible by the other elemental ray. Vast clouds of calcium seem to arise from the neighbourhood of sun spots, obscuring the calcium light coming from the regions below, while at the same time the hydrogen light from those regions is able to make good its escape.

Most of the dark lines of the solar spectrum are probably due to elements known on the earth, some imperfect coincidences being attributed to the difference in physical conditions, which, as we now know, affect the character of the spectral lines. The bright lines of the outer luminous layer or chromosphere, and of its attendant prominences, were first detected during eclipses, though with modern instruments they can always be seen at the edge of the sun's disc. A brilliant unknown line in the yellow was in

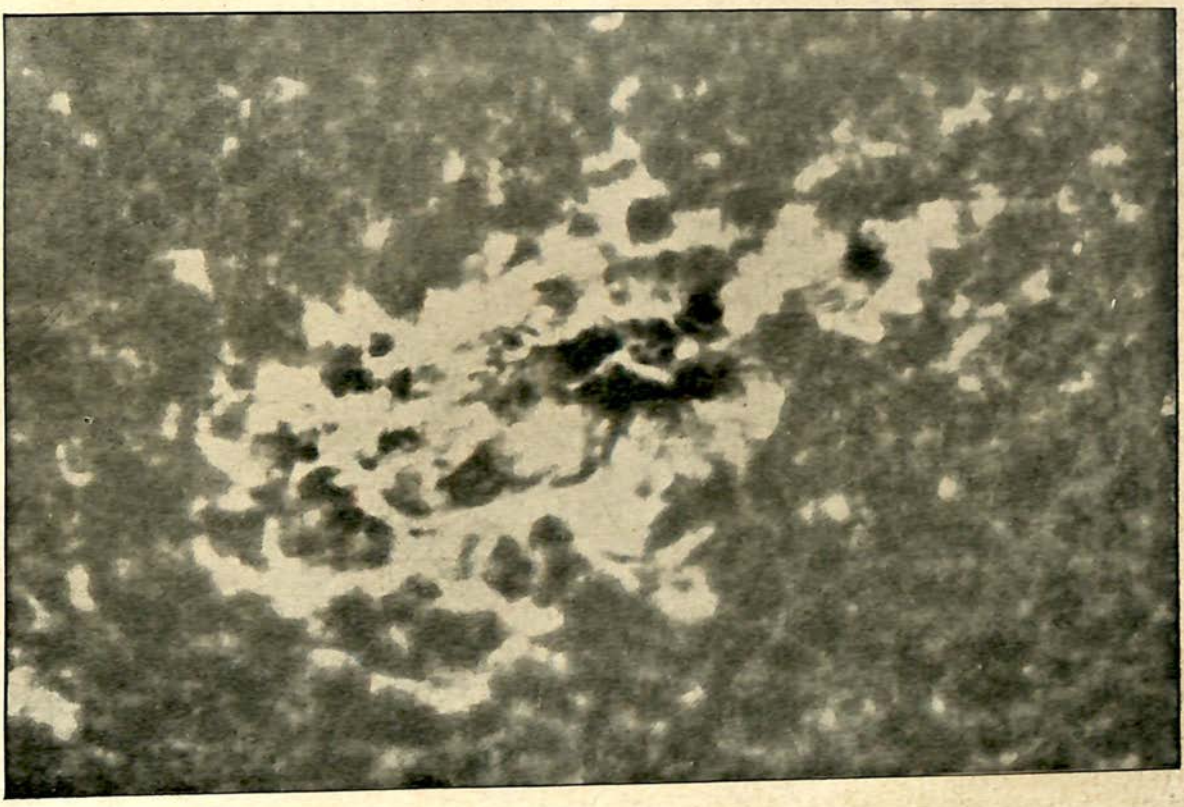


FIG. 37.—OCTOBER 9, $3^h\ 30^m$. CALCIUM FLOCCULI, $H_2$ LEVEL

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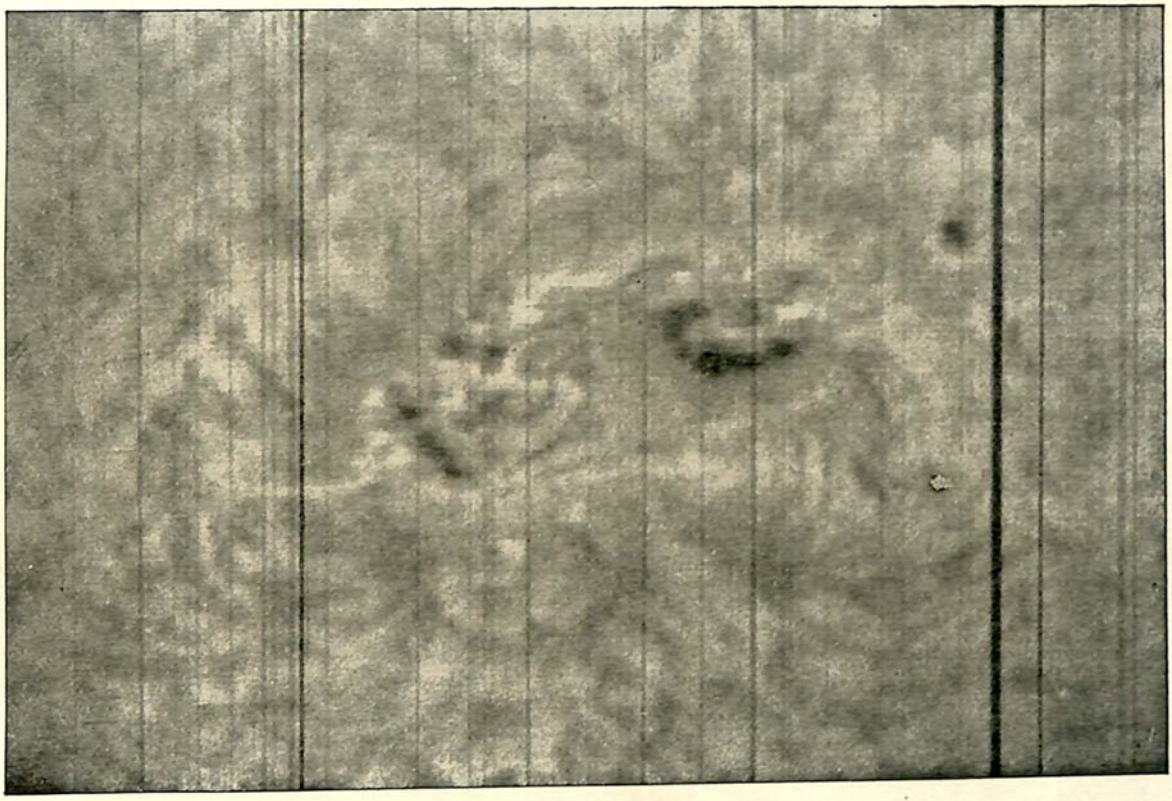


FIG. 38.—OCTOBER 9, $1^h\ 04^m$. HYDROGEN FLOCCULI

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1868 referred by Sir Norman Lockyer to a new element, to which was given the name of helium. In 1895 Sir William Ramsay detected the same spectrum by passing an electric spark through the gases evolved from a specimen of the mineral cleveite, and by this means isolated the gas helium, thus showing that the element, first discovered in the sun, was present also upon the earth. The complete spectrum of helium contains two sets of lines, one in the yellow and one in the green. In the laboratory these two sets are usually found together, though, by manipulating an electric discharge in helium, separation may be effected. In the light of the sun, too, the yellow line is sometimes found without the green. Other separations of the same kind between the constituents of the spectra of certain elements have also been observed, and have sometimes suggested the idea of atomic dissociation. Other explanations, however, seem, on the whole, more probable. Professor J. J. Thomson has shown that, when an electric discharge passes through rarified hydrogen, the red line becomes more intense near the positive and the green line near the negative electrode. This observation indicates a separation of hydrogen molecules into positive and negative parts, and is very suggestive in relation to solar physics.

During total eclipse, a vast radiance surrounding the sun, known as the corona, springs into view. Spectroscopic examination shows that hydrogen, helium, and calcium, the main constituents of the chromosphere, are absent in the corona. The principal part of the light seems to be due to a brilliant green line, not produced by any terrestrial substance. The hypothetical element emitting this light has been named coronium.

Although recent research has not yet led to a completely satisfactory conception of the general condition of the sun as a physical system, substantial progress in knowledge has nevertheless been made. The gigantic output of heat would be impossible for any solid globe, even if surrounded by a gaseous envelope. The external shell would cool too rapidly, unless a process of convection replaced the cooling gases on the surface by hotter ones from below. The temperature of the sun is above the critical points of most, at any rate, of known substances, and thus, although the pressures may be very high, liquids or solids are probably non-existent, except perhaps as clouds in the upper regions of the atmosphere. The best estimates of the temperature of the radiating part of the sun, based on the amount of solar heat received by the earth,

corrected for absorption, agree in indicating a temperature of about 6000° C.

A fairly general consensus of opinion had been reached to the effect that the source of the energy required for the sun's continual output of heat was to be sought in the mutual gravitating condensation of his parts. A mass of gravitating gas may become actually hotter by radiation. As it loses heat, its parts approach, and the whole mass contracts. Two bodies attracting each other will, by their collision, set free energy which appears as heat, and the mutual approach of the gravitating parts is an effect of the same kind. The heat thus developed may be more than enough to compensate for that lost by radiation. This reasoning was applied to the sun, and estimates of the sun's life as a useful radiating system were made by Lord Kelvin and others. But the past history of the sun was, on these calculations, far too short to admit of the periods required by the geologist and the biologist for the formation of the earth's crust and the evolution of species thereon.

The phenomena of radio-activity have, however, thrown new light on this problem. If but two or three parts in a million of the sun's mass consist of radium, Mr. W. E. Wilson has shown that the present rate of heat emission would be maintained. Thus a very small quantity of

radio-active material would appreciably retard the loss of heat, and greatly prolong the possible life of the sun. The spectrum of radium does not show in the sun's light, but, as laboratory experiments indicate, a large proportion of radium would be necessary to make visible its characteristic lines. On the other hand, the prevalence of helium suggests the occurrence of radio-active processes, during which, as we know, helium may be formed.

A similar lengthening of the probable age of the earth is also indicated by the same course of argument. The temperature of the earth rises as we pass underground, and, from the present temperature gradient, Lord Kelvin had calculated that about one hundred million years ago the earth was a molten mass. Although from the nature of the assumptions made in this calculation, little weight could be attached to the exact result obtained, the estimated age of the earth, as the home of organic life, was again too short for the requirements of geology and biology. But it is now known that radio-active matter in small quantities is very widely distributed throughout the earth and its atmosphere. Clay, for instance, yields a radio-active emanation in appreciable quantities, and Professor Rutherford has calculated that, if all the substance of the earth were

as active as clay, the present distribution of temperature might be maintained by this cause alone. Such a result shows, at all events, that the observed temperature gradient is not a safe guide when used as the sole means of estimating the age of the habitable globe.

The great advance in knowledge, recently gained by the study of the conduction of electricity through gases and the phenomena of radio-activity, cannot fail to exert a powerful influence on the future of astro-physics, and, in particular, on our conceptions of the nature of solar processes. The leak of electricity from hot bodies, studied in the physical laboratory, shows that corpuscles or electrons must be emitted in enormous quantities by the substance of the sun and hot stars. The likelihood of the presence of radio-active matter, too, and of the ejection of other corpuscles, with the transcendent velocities impressed on them by a radio-active origin, must not be forgotten. Although the corpuscles, before they reached the surface of the earth, would be absorbed by its atmosphere—equivalent as that atmosphere is to a thickness of thirty inches of mercury—they might produce striking phenomena in the regions of the upper air. Perhaps on these lines is to be explained the appearance of the

Aurora Borealis and kindred manifestations, while the luminosity of the solar corona may well have an electric origin. The application of the new discoveries of the laboratory to the problems of the heavens has hardly yet begun, but the region of investigation thus opened up must prove of almost illimitable extent, and the coming advance in its exploration will be followed with absorbing interest in the ensuing years.

The spectroscopic study of the stars has led to their classification into four main groups, clearly distinguished by Father Secchi. The first type consists of white stars showing the effects of strong helium and hydrogen absorption. The second give spectra crossed, like that of our sun, by innumerable fine metallic lines. The third type includes red stars with banded spectra, the bands being diffuse on their redder sides. In the fourth group are placed faint dark red stars, possessing wide bands in their spectra attributed to carbon. The addition of a fifth class, including stars with bright lines in their spectra, has been suggested by Pickering. Many subdivisions of these types have been recognised, and the variety and complexity of stellar natures seem endless.

It is impossible to resist the conclusion, however, that in this classification we have traced

the main outlines of the normal course of stellar evolution. In their youth, the suns seem to be surrounded with atmospheres principally consisting of helium and hydrogen. In their magnificent and turbulent prime, they are swathed in glowing robes of metallic vapour, still covered with the gauzy veil of helium and hydrogen. As they decline in vigour, their light grows redder, like that of a cooling iron bar. Of their ultimate condition, the same analogy, and the inferred existence of dark companions, give us some suggestion. Evidence, too, indicating the occasional possibility of a stellar resurrection is not withheld from us.

Many difficulties of interpretation still perplex the astronomer; observations accumulate and await explanation in increasing number. Nevertheless, it is probable that in some such life-history as this, we have already correctly formulated the true course of evolution of the majority of the stars.

The appearance of temporary stars is a phenomenon which has been observed repeatedly in historical times. Hipparchus, Tycho Brahe, and Kepler, for instance, have recorded such manifestations. But the first case critically examined by modern photographic methods was that of Nova Aurigæ, a star discovered in February 1892, the origin and growth of which were traced by subse-

quent examinations of photographs taken in the previous December and January, and preserved as part of the systematic photographic log-book of the heavens now kept by astronomers. For three months the star's brightness lasted and then rapidly it decreased, till at the end of April the Nova was barely visible in the great refracting telescope of the Lick Observatory. Soon afterwards, however, a faint nebula appeared in its place, with a quite different kind of spectrum.

More completely studied were the striking phenomena of the second Nova Persei, first sighted at Edinburgh in February 1901. Its rise and decline were followed in many places, particularly by Father Sidgreaves at Stonyhurst, and by Professor Campbell at the Lick Observatory. It attained its maximum brightness about a day and a half after its detection, and then grew fainter in a fluctuating manner for about ten days. Finally, a nebula was seen to develop, which increased in visible dimensions at a prodigious rate—so fast, indeed, that the most probable explanation supposes that the nebula was pre-existent but non-luminous, and was made visible by the flood of light released by the star. That light was reflected as it spread outwards from the centre in ever-widening spheres, and illuminated the scattered wisps of attenuated matter it encountered on its way

through space. Calculating from this assumption, it is obviously possible to deduce the distance of the star, which proves to be such that light would take about three hundred years to reach our eyes. It would follow that the phenomena we studied in the last days of Queen Victoria represented changes that were occurring in the depths of space while Queen Elizabeth occupied the throne of England.

When examined spectroscopically, the light of all the temporary stars yet investigated shows one remarkable property. Bright lines, displaced towards the red, are accompanied by dark lines of similar origin displaced towards the violet. Doppler's principle would indicate that the source of these double lines was a double star, the bright lines coming from a gaseous system emitting a line spectrum, and the dark lines from a partner star in which absorption was predominant. But the difficulties of such a view seem insuperable. The requisite velocities are of the order of some hundreds of miles a second, and no sign of periodicity or even diminution appears in their values. At one time it was thought that the temporary blaze of light might be due to the shock of collision of two stars meeting in space; but the doubling of the spectral lines indicates a common constitution unlikely invariably to be possessed by disconnected systems flying through the æther

from distant sources. On the other hand, the opposite velocities, constant in amount, show that the two stars cannot be two members of the same group, colliding with each other as an effect of ill-directed mutual gravitation, which would lead to a decrease in velocity as the stars, after collision, receded from each other. The theory of collision has perforce been abandoned. No satisfactory hypothesis has yet been proposed in its place. Perhaps the one least open to objection is that which regards the luminosity as due to the passage of a star, possibly a dark one, through the scattered matter constituting a nebula, in much the same way as a shooting star shines only during its transit through the earth's atmosphere.

Many years ago Clerk Maxwell showed theoretically that a stream of light, incident on a body, should produce a pressure in the direction of the advancing rays. Maxwell deduced the effect from the electro-magnetic theory of light, but it has since been shown by Larmor to be necessary on almost any wave theory. The undulating medium possesses energy, and, therefore, momentum. An absorbing body is gaining momentum, and therefore experiences a pressure in the direction of the incident beam. A reflecting body reflects the same momentum

back again, and therefore is acted on by a double pressure. This result has recently been confirmed experimentally by Professor Lebedef, of Moscow. The difficulties to be overcome are best appreciated by the statement that when bright sunlight falls on a reflecting surface, the pressure to be detected amounts to less than a milligramme per square metre. For an absorbing surface such as lamp black, the pressure is half as great as for a reflector, and it is the difference between these two effects that M. Lebedef has detected, the results of unequal heating and of molecular recoil being successfully eliminated. By another method the same pressure has still more recently been demonstrated by Nichols and Hull.

Owing to this pressure, two bodies radiating towards each other will experience a mutual repulsion, which, for small particles, may overcome the gravitational attraction. Even the attraction of the sun on a body may be neutralised if the body is of minute size, for the radiation effect depends on the area of surface, while the weight depends on the volume. As the size is diminished, the area decreases less rapidly than the volume, and, for microscopic particles less than 0.0001 millimetre in diameter, the radiative repulsion of the sun becomes greater

than the gravitational attraction. An interesting application of this principle has explained the curious phenomena of comets' tails, which have long puzzled the ingenuity of astronomers. If, as is probable, a comet consists of a collection of meteorites, varying in size from small worlds to microscopic particles, on approaching the sun the large masses will follow the parabolic path *ABC* (Fig. 39), indicated by the ordinary gravitational theory. Particles of the particular size at which the radiative force just balances that due to gravity will pursue a path, *ADE*, in an undeviated course, for both the forces vary inversely as the square of the distance, and will thus balance each other at all distances. Particles intermediate in size will follow intermediate paths, *AF*, *AG*, *AH*, &c. As the comet swings round the sun, the tail becomes expanded into the fan-like form commonly observed. The head of the comet goes on its way into the depths of space, having lost some of the smaller constituents of its tail, which are scattered throughout interplanetary regions.

Not only does the radiation from the sun cause a repulsion of small objects, but their radiation to each other will, as Professor Poynting has just recently shown, lead to a mutual

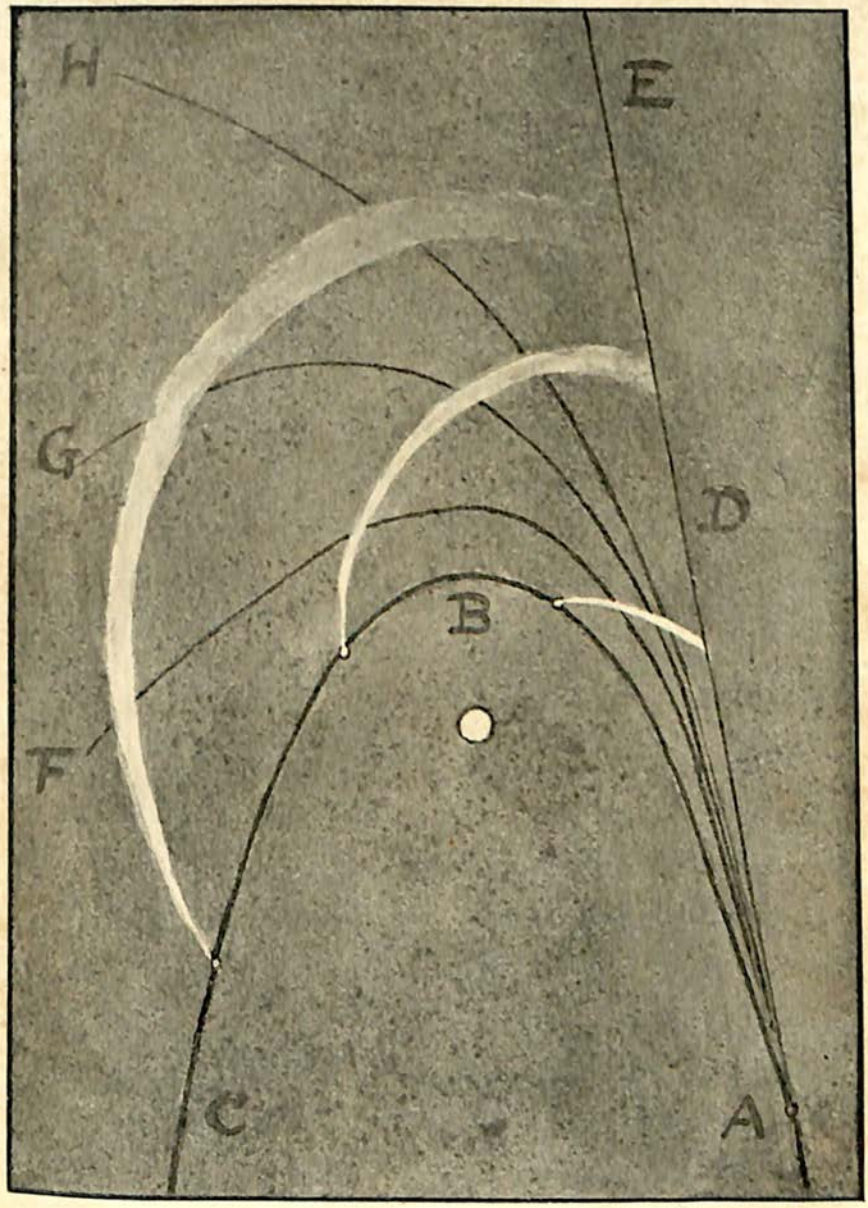



FIG. 39.—DIAGRAM TO EXPLAIN THE PHENOMENA OF COMETS' TAILS

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repulsion when the bodies are placed in a region of space where the effective temperature is lower than their own. Two meteorites at ordinary temperatures, say at 300° on the absolute scale, will in cold space repel each other with a force equal to their mutual gravitative attraction when their radii are about 3.4 centimetres, and, in the case of smaller bodies, the repulsion will overcome the gravitative effect. In this case, when the gravitational force is that between bodies of small mass, instead of that between some small body and the gigantic sun, a resultant repulsion is reached at much larger dimensions than those of the case formerly considered. It is evident that a swarm of meteorites of the right size might continue to revolve round a planet or sun without mutual forces and independently of each other. It is possible that this result has some bearing on the problem of Saturn's rings.

A curious conclusion may be drawn from the theory of the radiation-force between small bodies. Unless the temperatures are the same, the force on one need not necessarily be equal to the force on the other: action and reaction it seems are not equal and opposite. The inconsistency is, of course, prevented if we remember that the momentum of the æther must

also be taken into account. In reality each body is emitting a stream of momentum which exists for a while in the medium. In the interaction between that medium and either body, Newton's laws still hold. This is an example of the important part now played by the æther in physical conceptions. Its existence may be hypothetical, but its properties, hypothetical or not, are required to correlate the phenomena of the universe, and enter into the calculations in which the results of observation are expressed. Constantly the energy and momentum of the æther seem to be exchanged with those of ordinary matter, and to be just as much physical realities.

If we neglect the effect of the æther, there is no reason, in the case considered, why action and reaction should be equal and opposite. It is even possible to imagine the gravitation pull and the radiation push so adjusted that the accelerations become equal but in the same direction. The hotter body will then chase the colder body through space with constantly increasing velocity. A limit will, however, eventually be reached, for, owing to the Doppler principle, the waves in front of a moving body are crowded up, and those behind it lengthened out. The radiation-pressure in front is thus

increased, and that behind diminished, so that the net result is a retardation which tends to check the motion. In the case of meteorites small but yet large enough for the gravitative pull to be predominant, which are revolving round large bodies in orbits with high speeds, this retardation becomes important, and will eventually cause the meteorites to gravitate towards the centre. In this way it is possible that the sun may clear the neighbouring space of meteoritic dust, which would otherwise move round him in permanent orbits; and the earth would draw back to herself any particles shot out by volcanic eruptions, such as that of Krakatoa, when the velocities impressed may have been great enough to carry them beyond the atmosphere, and in the right direction to set them moving as satellites.

The theory of radiation also enables us to solve many other interesting problems connected with the solar system. By means of a thermodynamic proof it has been shown that the total radiation from a source should vary as the fourth power of the absolute temperature $T$, that is, as $T^4$. By experimental investigation it is possible to establish a numerical relation, and, if $R$ be the energy radiated per square centimetre per second by a full radiator such as

lamp black, the constant $k$ in the theoretical equation

$$R = kT^4$$

has been found by Kurlbaum to be about $5.32\ 10^{-5}$ erg.*

Now we can calculate the total energy radiated from the sun per second by measuring the amount received at the surface of the earth, and estimating the amount lost by reflection and absorption by the atmosphere. These considerations lead directly to the effective temperature of the sun, which is thus estimated to be from 6200° to 7000° absolute. Professor Poynting prefers the lower value, which means about 6000° C.

A small body, isolated in space, will, when a steady state is reached, radiate as much heat as it absorbs. If it be shielded from the sun, it will attain a temperature which may be considered to be the effective temperature of space. From estimates of the amount of heat received from the stars, as compared with that received from the sun, Poynting calculates the effective temperature of space to be 10° absolute, or 263° C. below the freezing-point of water.

* The erg is the French unit of work or energy. About an erg of work is done when the thousandth part of a gramme is raised through one centimetre.

Similar principles give a basis for a determination of the temperatures of planets at any given distance from the sun. Assuming that all the heat absorbed is eventually radiated out again, and that about one-tenth of the incident heat is reflected, and making certain simplifying assumptions, the mean temperature of the surface of the earth is calculated as 290° absolute, or 17° C. The average temperature of the earth's surface is known to be about 60° F., or 16° C. The calculation is made on the assumption that the effective temperature of the sun is 6200° absolute, and its concordance with observation is the ground given by Poynting for prefering that value for the solar temperature.

This success in calculating the effective temperature of the earth lends weight to the values given by the same method for the temperatures of the other planets. Mercury and Venus, with orbits inside that of the earth, possess temperatures of 194° and 69° C. respectively, while the outer planets, Mars and Neptune, fall as low as −38° and −221°. If there are, indeed, inhabitants on Mars, it seems that, according to terrestrial ideas, they must lead a very chilly existence.

When any branch of learning first finds itself

in a position to use the methods and accumulated experience of another science, a period of striking discoveries may confidently be anticipated. Thus it was that Newton applied to the phenomena of the heavens the mechanical knowledge of previous ages, and the law of gravity revealed the harmony of the spheres. When it was found that the generalisations of thermodynamics and of electrical science could be used in chemical problems, a new world opened before the investigator. So it is with the transfer of physical methods and data to the problems of astro-physics. The first-fruits of this harvest of knowledge have already proved of momentous import, and in the combination of physics and astronomy the present labourers and those that come after them may hope to find one of the most fertile unions in the whole realm of Natural Philosophy.

# *A List of Books*

*in which may be seen further particulars of the subjects discussed in this volume*

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CHAPTER I.—**The Philosophical Basis of Physical Science.**

Die Mechanik in ihre Entwickelung, by E. MACH; an English translation by T. J. M'CORMACK has appeared.

CHAPTER II.—**The Liquefaction of Gases.**

Article on Liquid Gases, by Sir J. DEWAR, in the Supplement to the "Encyclopædia Britannica."

CHAPTER III.—**Fusion and Solidification,** and

CHAPTER IV.—**The Problems of Solution.**

The Theory of Solution, by W. C. D. WHETHAM.

CHAPTER V.—**The Conduction of Electricity through Gases.**

Conduction of Electricity through Gases, by J. J. THOMSON.

CHAPTER VI.—**Radio-Activity.**

Radio-Activity, by E. RUTHERFORD.

CHAPTER VII.—**Atoms and Æther.**

Electricity and Matter, by J. J. THOMSON.
Æther and Matter, by J. LARMOR.

CHAPTER VIII.—**Astro-Physics.**

Problems in Astro-Physics, by Miss A. CLERKE.

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